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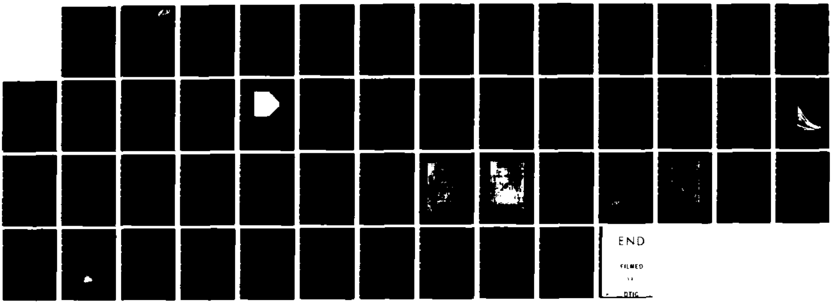

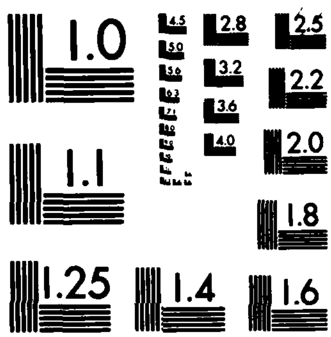

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A New Characterization of Supercooled Clouds Below 10,000 Feet AGL

Charles O. Masters

June 1983

Final Report

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US Department of Transportation
Federal Aviation Administration
Technical Center
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16. Abstract

Icing envelopes which effectively characterize supercooled clouds from ground level to 10,000 feet above ground level over the conterminous United States have been generated from a new data base of aerial observations. This data base, recently established via an Interagency Agreement between the FAA and the Naval Research Laboratory is the largest, most significant compilation of low-altitude supercooled characteristics currently in existence. It is intended that this new characterization serve as a basis for the establishment of design criteria and regulations that pertain to ice protection systems and equipments for low performance aircraft which typically operate below 10,000 feet. This new characterization groups the supercooled cloud properties for all cloud types observed into three temperature ranges and presents their associated values of liquid water content (LWC), range of median volume droplet diameters (MVD), and icing event duration. Details of the analysis process are discussed which use a least squares logarithmic regression estimation technique to predict the extreme values of supercooled cloud properties.

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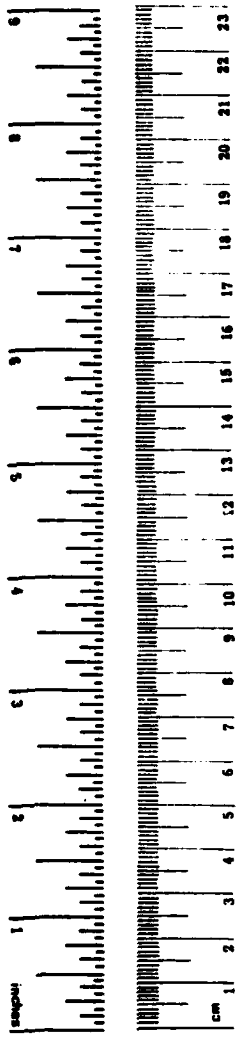
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

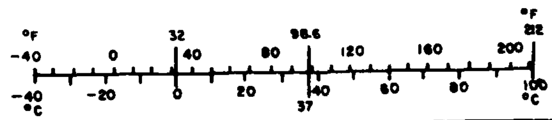
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

The Federal Aviation Administration (FAA) has sponsored the gathering of atmospheric icing data to be used in the establishment of a new characterization of supercooled clouds below 10,000 feet above ground level (AGL). This effort has culminated in the establishment of a data base containing an extensive archiving of aerial observations in supercooled clouds. This data base encompassing about equal amounts of modern observations and historic National Advisory Committee for Aeronautics (NACA) observations in both layer and convective clouds is deemed the largest, most significant, compilation of low-altitude supercooled cloud characteristics currently in existence. The preponderance of this work has been performed by Dr. Richard K. Jeck of the U.S. Naval Research Laboratory (NRL). The author, in the creation of the new criteria, has used these data extensively, and has received invaluable assistance from Dr. Jeck in the process. The author hereby acknowledges the important role fulfilled by Dr. Jeck throughout this effort and especially for his roles in establishing the atmospheric icing data base and in the computation of the percentiles which were essential to the determination of the extreme values of the cloud properties. Also, the author is indebted to Mr. James E. Newcomb of the FAA Technical Center's Aircraft and Airport Systems Technology Division for his assistance rendered in the area of computer graphics. Last but not least, the author is indebted to Mr. Ernest E. Schlatter, Research Meteorologist and acting Aircraft Icing Program Manager at the FAA Technical Center for his perceptive guidance throughout this endeavor.

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LIST OF ABBREVIATIONS

AGL	Above Ground Level
°C	Degrees Celsius
FAA	Federal Aviation Administration
FAR 25	Federal Aviation Regulations, Part 25
gm^{-3}	Grams per Cubic Meter
IA	Interagency Agreement
inHg	Inches of Mercury
kts	Knots
LWC	Liquid Water Content
MED	Mean Effective Diameter
MRI	Meteorology Research, Incorporated
MVD	Median Volume Diameter
MSL	Mean Sea Level
N	Cloud Droplet Concentration
NACA	National Advisory Committee for Aeronautics
nmi	Nautical Mile
NRL	Naval Research Laboratory
PA	Pressure Altitude
PMS	Particles Measuring Systems, Incorporated
R	Correlation Coefficient
RMC	Rotating Multicylinder
Ta	Ambient Temperature
TN	Technical Note
μm	Micron; one Millionith of Meter
USAF	United States Air Force
UWA	University of Washington (Seattle)
UWY	University of Wyoming

GLOSSARY

Convective Cloud	Clouds of moderate to extensive vertical development; also termed "heap clouds." The convective cloud types comprise cumulus and cumulonimbus.
Data Mile	The distance flown in nautical miles during an icing event.
Icing Encounter	A series of icing events consecutively penetrated until an interruption of more than some selected distance such as 1, 3, or 10 nautical miles is experienced.
Icing Event	A portion of a subfreezing cloud over which portion the cloud properties are approximately constant as defined by the 'Rules for Defining Icing Events' in appendix B.
Layer Cloud	Clouds of no marked vertical development; also termed "sheet clouds." The layer cloud types comprise cirrus, cirrocumulus, cirrostratus, altocumulus, altostratus, nimbostratus, stratus, and stratocumulus.
Liquid Water Content (LWC)	The total mass of water contained in all the liquid cloud droplets within a unit volume of cloud. Units of LWC are usually grams of water per cubic meter of air (gm^{-3}).
Median Volume Diameter (MVD)	The median of the cloud droplet size distribution computed after weighting each droplet size by its volume. The MVD divides the LWC of the droplet population in half according to droplet size.
Orographic Cloud	A cloud which is formed by forced uplift of air over high ground. Stratus, cumulus, and cirrus clouds can be of orographic origin.

EXECUTIVE SUMMARY

Since 1979, the United States (U.S.) Naval Research Laboratory (NRL) under inter-agency agreement Number DOT-FA79WAI-020 with the Federal Aviation Administration (FAA) has been accumulating and cataloging data on the properties of low-altitude supercooled (subfreezing) clouds which occurred over the conterminous United States and nearby off-shore areas.

This effort has culminated in the establishment of a data base containing over 6,700 miles of aerial observations in supercooled clouds. This data base encompassing about equal amounts of modern observations and historic National Advisory Committee for Aeronautics (NACA) observations in both layer and convective clouds is deemed the largest most significant, compilation of low-altitude supercooled cloud characteristics currently in existence. This data base was essential to the creation of the new characterization of supercooled clouds of this report.

It is intended that this new characterization be used in the establishment of design criteria and rules and regulations as they pertain to ice protection systems and equipment for aircraft which typically operate below 10,000 feet. The existing criteria currently being applied to all aircraft seeking U.S. certification, is promulgated in Federal Aviation Regulation (FAR) 25, appendix C, and has been deemed excessively conservative by versed users.

This report addresses the data analysis and rationale associated with the creation of the new characterization from the aforementioned data base. The new characterization groups the supercooled cloud properties for all observed cloud types into three temperature ranges of 0 to -15° C, -15 to -20° C, and -20 to -25° C, and presents the associated values of liquid water content (LWC), median volume droplet diameter (MVD), and icing event duration. The extreme values for the three temperature ranges are:

Temperature Range (°C)	LWC Range (gm^{-3})	MVD Range (μm)	Event Duration (nmi)
0 to -15	.04 to 1.74	3 to 50	6 to 50
-15 to -20	.04 to .66	5 to 38	20
-20 to -25	.04 to .41	7 to 15	20

Follow-on efforts, as currently planned, will extend this characterization to all worldwide flyable altitudes and will encompass other atmospheric phenomena conducive to aircraft icing; i.e., freezing rain, drizzle, mixed conditions, and snow.

INTRODUCTION

PURPOSE.

The purpose of this report is to document data reduction and data analysis processes utilized in the generation of a new characterization of super-cooled clouds from sea level to 10,000 feet above ground level (AGL). It is intended that the information presented herein be used in the establishment of design criteria and regulations for ice protection system and equipments for appropriate aircraft and by organization and agencies to generate and duplicate this new characterization as required.

BACKGROUND.

The Federal Aviation Administration (FAA) currently requires that aircraft manufacturers seeking United States (U.S.) certification of their aircraft for flight into known icing conditions show compliance with the icing criteria requirements of Federal Aviation Regulation (FAR) Part 25, appendix C (see reference 1). These criteria, based upon data developed by the National Advisory Committee for Aeronautics (NACA) in the late 1940 to early 1950 time frame were intended primarily for large high performance fixed wing aircraft and encompassed both layer and convective clouds with altitudes from 0 to 22,000 feet (PA), suggested temperatures as cold as -40° C, and liquid water content (LWC) as high as 2.9 gm^{-3}. Since their generation, these criteria have been exacted upon all aircraft seeking U.S. certification for flight into known icing conditions, including both rotary and fixed wing, low altitude, low performance aircraft which typically operate below 10,000 feet.

Realizing the possible asperity of this approach, the FAA in 1979, under interagency agreement (IA) number DOT-FA79WAI-020, engaged the Atmospheric Physics Branch of the Naval Research Laboratory (NRL) to conduct studies to develop a better characterization of the atmosphere below 10,000 feet as it pertained to aircraft icing. Preliminary results of this effort are reported in the FAA Report Number FAA-RD-80-24, entitled, "Icing Characteristics of Low Altitude, Supercooled Layer Clouds" (reference 2). Being preliminary in nature, this report presented a review of the historical NACA data used in generating FAR 25, appendix C, and discussed the rotating multicylinder (RMC) measurement technique employed in obtaining measurements of the clouds LWC and droplet sizes. Also, it addressed limited results obtained from NRL icing survey flights conducted in early 1979. However, the final data base utilized in generating the new characterization of supercooled clouds below 10,000 feet AGL is contained in the NRL Report Number DOT/FAA/CT-83/21 entitled, "A New Data Base of Supercooled Cloud Variables at Altitudes below 10,000 feet AGL and the Implications for Low Altitude Aircraft Icing" (reference 3).

This compilation of data collected primarily over the conterminous United States addresses layer and convective supercooled clouds and includes some documentation on orographic, lake effect, and maritime clouds. These data, compiled from various private, university, and government concerns, were taken in various winter time synoptic weather phenomena conducive to aircraft icing.

Once collected, these data were analyzed and a means devised for presenting the results in a concise unambigious manner. This report presents the rationale, data analysis, and data reduction procedures employed in the generation of the of the icing envelopes and t.e other information which constitute the new characterization of supercooled clouds below 10,000 feet AGL.

DISCUSSIONS

THE DATA BASE.

The data base used in this analysis is well documented in reference 3 and consists of some 6,700 plus miles of aeronautical observations encompassing ≈ 1400 icing events in which the values of LWC, droplet size (MVD or MED), ambient temperature (Ta), and icing event duration were obtained. Approximately one-half of these data were compiled from modern observations with the remaining half from the historic (NACA) observations.

The historic data was obtained using rotating multicylinders as the primary instrument for determining MED and LWC, whereas the modern data was obtained using Particle Measuring Systems, Incorporated (PMS) cloud droplet spectrometers and other cloud physics instrumentation. All data used in this analysis were catalogued under either layer or convective cloud types (see glossary) and included data from observations conducted by NACA, the U.S. Air Force (USAF) Geophysical Laboratory, the University of Wyoming, the University of Washington, Meteorology Research, Incorporated (MRI) (via the U.S. Army), and NRL. Scatter plots of the icing events in raw data form are contained in appendix C.

GENERAL APPROACH.

The basic approach employed in these analyses for the new characterization was to determine values of LWC, MVD, Ta, and event duration such that the probability of independently exceeding any one of these parameters would be less than one part in a thousand; i.e., <.001 for all atmospheric icing conditions up to 10,000 feet AGL over the conterminous U.S. and nearby offshore areas. The initial analysis effort consisted of reviewing all icing events in raw data form in 5° C temperature increments from 0 to -25° C for each parameter of interest. These parameters were then ordered by magnitude and the 99.9 percentile selected.[1] Thus, values which exceeded the 99.9 percentiles would correspond to values of those parameters with a probability of exceedance less than 1 part in a thousand. Obviously, such a simplistic approach could only be employed and yield results with a high level of confidence in cases where there is a symmetrical, unimodal, near infinite data set from which to draw. However, in this case, the data base of 6,700 plus data miles representing some 1400 icing events was deemed marginal, especially for extreme parameter values which were typified by limited data miles.

Conditional probabilities of exceedance; i.e., the probability that some extreme value of a parameter of interest will exceed its 99.9 percentile value given a conditional probability of another parameter were not addressed in this analysis. However, realizing the possible limitation of the raw data set, a least squares logarithmic regression estimation technique based upon the Weibull distribution was employed to predict the extreme values at the 99.9 percentiles. This approach is discussed elsewhere in the report.

[1]This approach is documented in several texts on engineering statistics; e.g., "Probability and Statistics for Engineers," I. Miller and J. Freund, Prentice Hall, Incorporated, 1965.

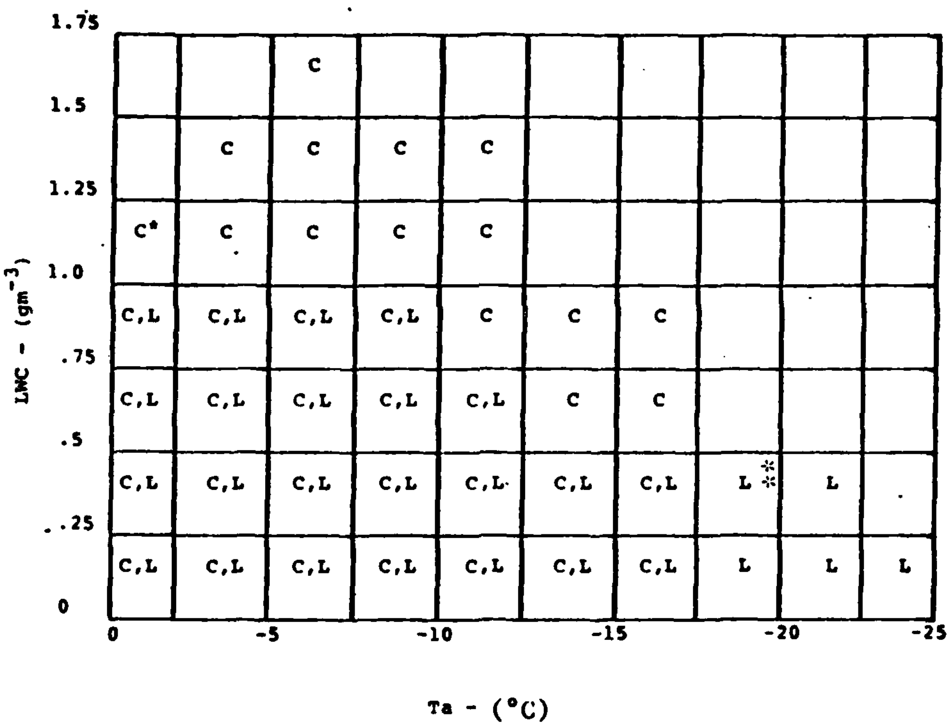
UNITS OF MEASURE.

The basic unit of measure of these data is the "icing event" and represents a portion of a supercooled cloud over which the cloud properties are approximately constant and PA does not change more than $\pm$ 500 feet (see glossary for a detailed definition). These properties encompass values of MVD, or MED, Temperature (Ta), event duration, and droplet concentrations (modern data only). Other parameters of interest include pressure altitude (PA), altitude above ground level (AGL), altitude above mean sea level (MSL), aircraft spatial information, aircraft velocity, and meteorological descriptions. The new characterization is constructed from values of LWC, MVD/MED, Ta, and event duration. During the modern data gathering process, in most cases, separate values of LWC were simultaneously determined from PMS probe measurements and from Johnson-Williams hot wire type probe measurements. In these cases, the higher (more conservative) LWC values of these two measurements were used in these analyses. Appendix B presents a detailed list of cloud properties limits and rules used in defining an icing event. The basic unit for defining the duration of an icing event in these data is the "data mile." This term is defined as the distance flown during a single icing event and is expressed in nautical miles (nmi) (see glossary). Rationale for the use of data miles to "weight" an icing event as opposed to the "number of icing events" to represent the extent or frequency of occurrence is presented in reference 3.

A COMBINED PRESENTATION FOR LAYER AND CONVECTIVE CLOUDS.

In FAR 25, appendix C, the presentations of LWC, temperature, MVD, and horizontal extent (duration) are presented separately for layer clouds (continuous maximum conditions) and for convective clouds (intermittent maximum conditions). The basis for specifying the values of LWC, Ta, and MVD as design criteria for aircraft ice protection equipment is discussed in NACA TN 1885 (reference 5), whereas the rationale for the values of horizontal extent and the cloud liquid water content factor are discussed in NACA TN 2738 (reference 4). In fact, TN 1855 presents rationale for three classes of meteorological conditions relating to supercooled clouds which could affect ice protection equipment design. These conditions range from an instantaneous maximum at one extreme to a continuous normal at the other. The instantaneous maximum was typified by summer time, tropical, towering, cumlus clouds with tops as high as 30,000 feet and LWC's up to 5.0 gm^{-3}. The continuous normal condition was typified by layer clouds with LWC's which ranged from < 0.1 gm^{-3} to 0.5 gm^{-3}, and a single MVD centered around 15 µm and altitudes on the order of 3,000 to 20,000 feet. However, these two extreme cases of the classes were not included in FAR 25, appendix C, although it did include the intermittent maximum and the continuous maximum classes which were viewed as those cloud types containing maximum icing conditions that were most probable of being encountered over the U.S. during winter time icing conditions. A copy of this criteria is included as appendix A.

A review of the new characterization data base in terms of layer clouds versus convective clouds indicate that the ranges of cloud properties were similar for both cloud types except for LWC's > 1.0 gm^{-3} which were found only in convective clouds and for Ta colder than -17.5° C where only layer clouds were observed. This is delineated in the matrix of figure 1 which shows Ta versus LWC for each cloud type. Thus, initially, it could be surmised that combining the cloud types data into one presentation would not be unduly restrictive due to their similarity. Obviously, this approach could not be taken during the generation of the FAR 25, appendix C, criteria. The one parameter demanding further attention in this approach is that of horizontal extent (icing event duration). It is evident that for LWC's > 1.0 gm^{-3} the characterization for horizontal extent should be based upon only convective cloud data and should not be contaminated with layer cloud values which occurred at the lower LWC's. Conceivably, this misrepresentation could occur if one chose a LWC range of say .75 to 1.75 gm^{-3} to determine the extreme value of horizontal extent. Since the longer event durations of the layer clouds in the .75 to 1.0 gm^{-3} range would dominate, characterization of this range would include both high LWC's and moderately long event durations that would not be supportable by observed data. For the range of LWC between 0 and 0.5 gm^{-3} and Ta colder than -17.5° C, the horizontal extent exhibited by the layer clouds compared favorably with those at Ta warmer than -17.5 °C. Although in some cases the layer cloud extents were moderately longer than those associated with the convective clouds, these differences were not viewed as being significant enough to warrant separate layer and convective cloud presentations. Thus, it was concluded that combining the data of the two cloud types into one overall graphical presentation could be accomplished without undue penalties being imposed upon either data set. Consequently, this was the approach taken.



*C = Convective Cloud

*L = Layer Cloud

FIGURE 1. MATRIX OF LWC VERSUS AMBIENT TEMPERATURE (T_a) FOR CLOUD TYPES

A CONSOLIDATED TEMPERATURE RANGE: 0 to -15° C.

Initially, raw data graphs were constructed for each of the 5° C temperature intervals between 0 and -25° C in a manner similar to the LWC versus MED graphs of FAR 25, appendix C. The maximum observed values of LWC which occurred in each 5 μm interval of MVD was used to establish an interim envelope outline for each of the temperature ranges. The one exception is the one lone maximum data point which occurred at 22 μm at a LWC of 1.7 gm^{-3} and a Ta of -6.5° C that was omitted from the interim envelopes. These raw data graphs revealed very little differences between the three envelopes in the 0 to -15° C temperature interval. Maximum deviations between envelopes were on the order of 20% with deviations of 5-10 percent being typical. A combined graph of these three temperature intervals is depicted in figure 2. Consequently, it was decided to combine all data in the 0 to -15° C temperature range and establish one envelope which described these parameters. Rationale for the inclusion of the one lone data point of 1.7 gm^{-3} to this temperature range could be supported if, during subsequent analysis, this point was found to lie within the 99.9 percent percentile since it occurred at -6.5° C, the ≈ midpoint of the 0 to -15° C temperature band. This semblance was not observed in the temperature ranges of -15 to -20° C and -20 to -25° C. Consequently, parameters in these ranges were treated separately. Thus, the new characterization would have three temperature ranges; i.e., 0 to -15° C, -15 to -20° C, and -20 to -25° C, which presented LWC versus MVD in a manner analogous to that employed in FAR 25, appendix C.

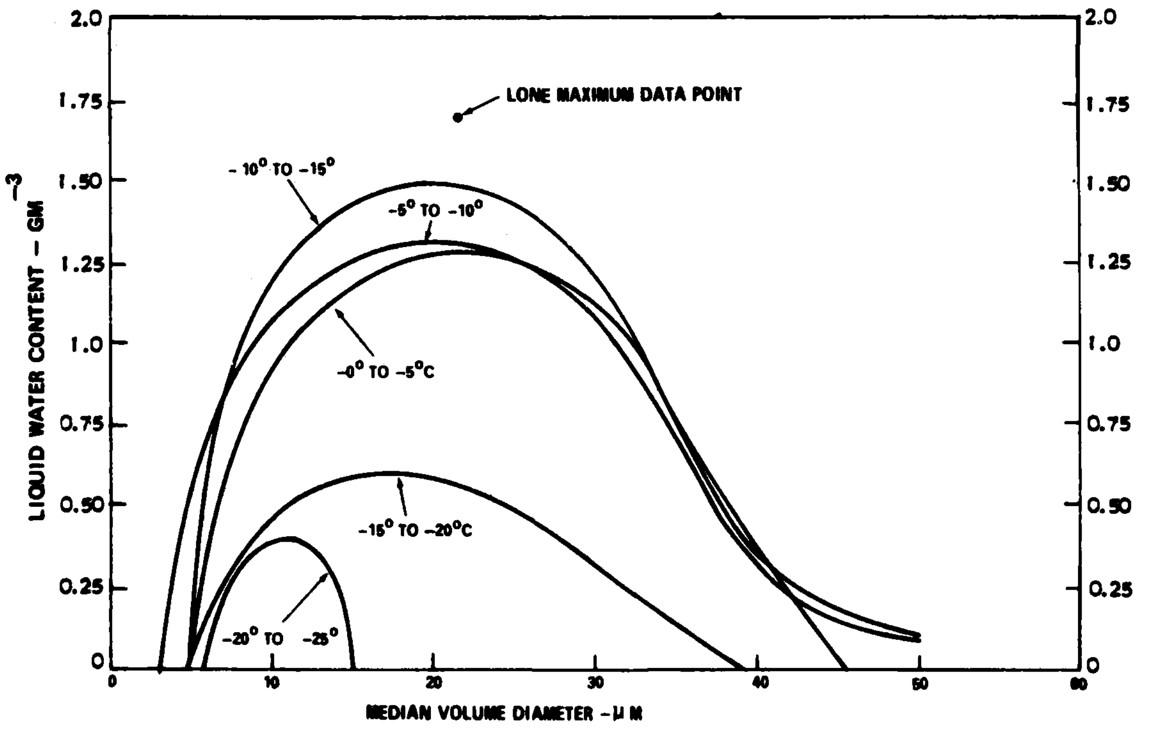


FIGURE 2. SIMILARITY OF ICING ENVELOPES OF 5° C INTERVALS FOR THE TEMPERATURE RANGE OF 0 TO -15° C

HORIZONTAL EXTENT: A STANDARD DISTANCE.

In gathering the data which formed the base for FAR 25, appendix C, the use of RMC's to determine the cloud properties of LWC and MED resulted in an average observation distance of about 3 miles for observation in cumulus clouds and about 10 miles in layer clouds. During subsequent analyses by NACA, these distances were characterized as being standard; i.e., a horizontal extent of 3 miles in intermittent cumulus clouds conducive to maximum icing conditions and a horizontal extent of 10 miles in continuous layer clouds conducive to maximum icing conditions (reference 5). The values of MED and LWC determined by this method typically represented maximum values since attempts were made to obtain the measurements during the exposure periods when the accretion of ice was most rapid. Also, during the measurement process, attempts were made to obtain samples from clouds in which the standard distances could be maintained without discontinuities (gaps) during the entire sample period.

Since most of the flight paths were chosen with the intent of maximizing the severity and extent of the icing encounter, the resulting horizontal extents were not necessarily representative of those that would be encountered by transport aircraft during typical air carrier operations. The NACA probability analysis of TN 2738 subsequently recommended a standard distance of 20 statute miles for the horizontal extent in layer clouds. Thus, FAR 25, appendix C, currently promulgates standard distances of 3 statute miles for cumulus clouds and 20 statute miles for layer clouds.

The approach taken in the new characterization relative to horizontal extent differs in that, during the measurement processes for the modern data, there was no need to use a standard distance. Consequently, data were taken and characterized for each icing event as long as the criteria of appendix B were met. By definition, each icing event consisted of continuous data and, in most cases, was terminated when LWC and/or cloud droplet concentrations changed by 50 percent from a median value. Thus, the modern data consists of approximately 940 separate icing events, several of which originated from the same icing encounter or icing cloud, but none of which has a standard distance. Before integrating the 360 plus NACA icing encounter data samples into the new data base, it was necessary to screen several data sets to separate out individual events that had been characterized as a single icing encounter. In final analysis, individual icing events from the modern and NACA data were employed in establishing the horizontal extent for the new characterization.

TEMPERATURE VERSUS ALTITUDE.

Construction of a graph to represent the supercooled cloud properties of LWC, Ta, MVD, and duration over the range of 0 to 10,000 feet AGL could take many directions in 2 or 3 dimensional form. An initial review of the data base indicated no appreciable altitude dependence for the cloud properties of LWC and MVD. However, icing conditions were not observed at the colder temperatures which occurred at the higher and lower altitudes; i.e., temperature in the range of -15 to -25° C which occurred between ground level and 4,000 feet AGL and between 6,000 feet and 10,000 feet AGL (figure 3). However, this region constituted only a small portion, approximately 16 percent of the total temperature versus altitude envelope and for all practical purposes could be accommodated by assuming the probable existence of supercooled clouds at all temperatures of interest and at all altitudes up to 10,000 feet AGL. (Possibly over the northern most portions of the U.S. during outbreaks of extreme cold polar air masses.)

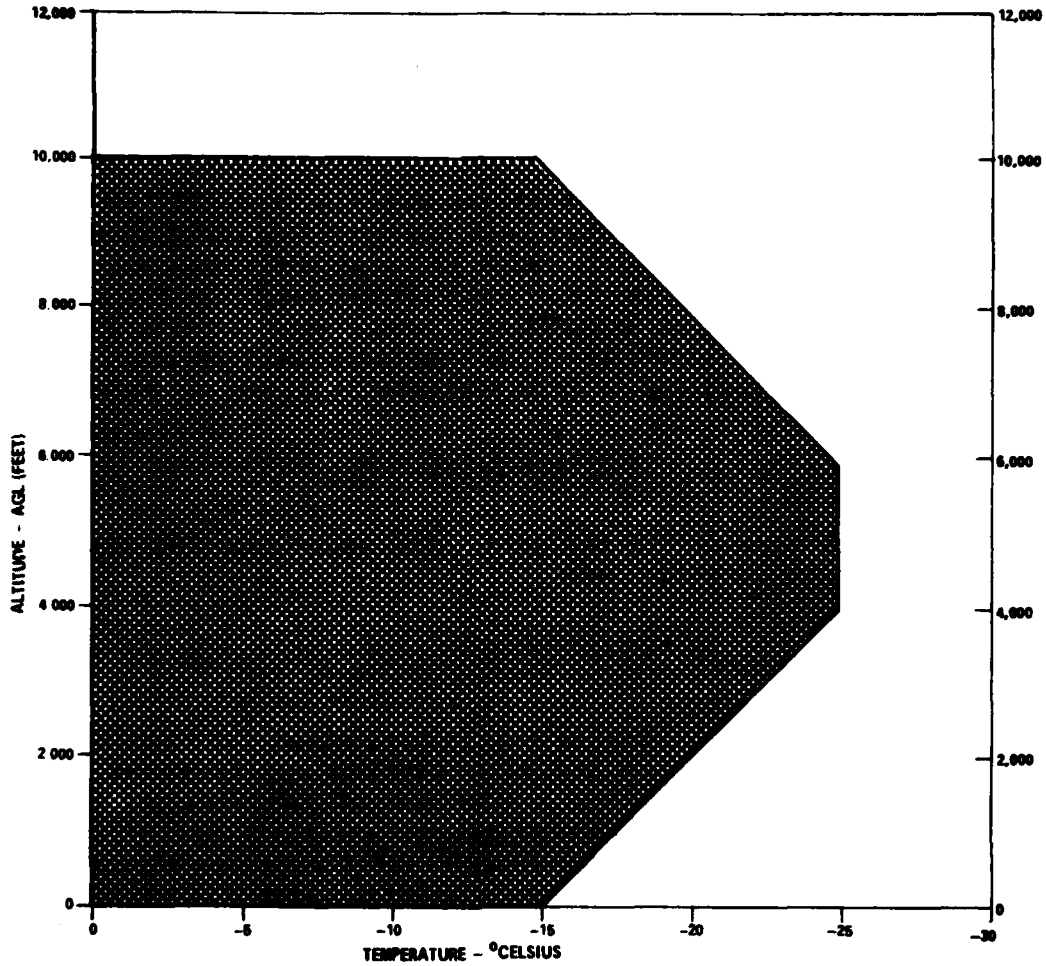


FIGURE 3. AMBIENT TEMPERATURE VERSUS ALTITUDE ABOVE GROUND LEVEL FOR OBSERVED SUPERCOOLED CLOUDS

Such assumptions could not be made without undue penalties in the case of FAR 25, appendix C, due to its altitude extremes of 0 to 29,000 plus feet and the associated temperature excursions. Consequently, the new characterization does not present a temperature versus altitude chart whereas FAR 25, appendix C, presents such a chart for both the continuous maximum and intermittent maximum criteria.

THE WEIBULL DISTRIBUTION VERSUS GUMBEL DISTRIBUTION.

The Gumbel distribution has long been used as a basis for predicting extreme meteorological values. This distribution espoused by E. J. Gumbel in reference 7 was employed by Lewis and Bergrun in their treatise on the probability analysis of meteorological factors conducive to aircraft icing (reference 4) which in turn gave rise to the LWC factor versus cloud horizontal extent curves employed in FAR 25, appendix C. This distribution has the property that cumulative probability distribution curves representative of meteorological variable will appear as a straight line when plotted on Gumbel paper (linear versus natural log x natural log). The Gumbel distribution given by the equation

$$P_g(x) = 1-e^{-e^{-\alpha(x-\mu)}} \tag{1}$$

where α is a quantity which establishes the scale of the distribution about the off-set or minimum value parameter (μ), was employed initially in the analysis to predict the maximum probable 99.9 percentile value of horizontal extent for several ranges of LWC within each of the three temperature ranges. The cumlative probability values (percentiles) of horizontal extent, when plotted in Gumbel coordinates, did not yield straight lines as had been anticipated, instead curves of a logarithmic nature resulted. This suggested the use of an equation of the form

$$P(x) = 1-e^{-e^{-k \log (\alpha(x-\mu))}} \tag{2}$$

to achieve a straight line fit of the data. The above equation (2) after simplification can be shown to take the form

$$P_w(x) = 1-e^{-\alpha(x-\mu)} \tag{3}$$

which is readily recognized as the Weibull distribution function and it has been used extensively in reliability and life testing applications. To a lesser degree, it has been employed in the prediction of the smallest values and the extreme values of the engineering properties of materials and of certain natural phenomena (reference 8). When the horizontal extent data was replotted in Weibull coordinates, employing linear regression, a straight line fit with a high coefficient of correlation (R), >.95 resulted for each of the data set. Similar results were obtained when initial calculations were performed to determine the extreme temperature values. Consequently, it was decided to employ the Weibull distribution in lieu of the Gumbel distribution in these analyses where warranted. Details of the Weibull variables employed in the subsequent analyses is presented in appendix D.

THE DETERMINATION OF HORIZONTAL EXTENT EXTREMES.

As discussed earlier, the NACA data and the modern data were combined into a single data set and then separated into three temperature ranges of 0 to -15° C, -15 to -20° C, and -20 to -25° C. Data within each temperature range was then analyzed to determine the one part in a thousand exceedance probability for event duration. For the two colder temperature ranges, all of the data within each temperature range was treated as a group and the values of horizontal extent were ordered as a function of data miles with the shortest icing event at the bottom of the order and the longest icing event accompanying the highest order. Values for the 20, 50, 60, 80, 90, 95, 99, and 99.9 percentiles were then obtained and plotted in Weibull coordinates.

The Weibull distribution function from equation (3) reduced to the form

$$\ln (X_i) = \ln \ln \left(\frac{1}{1-P_i}\right) \tag{4}$$

was employed to establish the coordinates of the plot: Where

P_i = the percentile of interest; i.e., 20, 50, 60, . . . 99.9

X_i = the horizontal extent value in nautical miles associated with the i th percentiles.

After plotting, a least-squares linear regression analysis was performed to determine the straight line of best fit. Once established, the straight line of best fit was used to determine the Weibull 99.9 percentile value which, in most cases, exceeded the 99.9 percentile value from the observed data. (The Weibull 99.9 percentile value was typically rounded off to the nearest whole number to eliminate fractions.) This Weibull 99.9 percentile value was then representative of that horizontal extent of a supercooled cloud (in nmi) which would probably not be exceeded more often than 1 time in 1,000 icing event encounters.

In a similar manner, the 99.9 probability of exceedences for the horizontal extents in the temperature range of 0 to −15° C was determined, except data in this temperature range was subdivided into four groups as a function of LWC before being ordered. The four groupings were:

0 to 0.5 gm^{-3}, 0.5 to .75 gm^{-3}, .75 to 1.0 gm^{-3}, and >1.0 gm^{-3}

This subdivision was deemed appropriate since the extreme event durations (exhibited by the raw data) were relative short for the LWC groups > 1.0 gm^{-3} (all cumulus clouds), were moderately long for the LWC grouping of 0 to 0.5 gm^{-3} and showed a 60 to 70 percent difference in value associated with the two mid-ranges. Table 1 presents the percentile data and resulting Weibull 99.9 percentile values for horizontal extents.

TABLE 1. HORIZONTAL EXTENTS PERCENTILES

TEMPERATURE		DATA MILES	PERCENTILES 50	60	80	90	95	99	99.9	WEIBULL 99.9	RECOMMENDED VALUE	R*
			NAUTICAL MILES									
0 to −15°C												
LWC	0−.5	5540	2.5	3.2	8.2	12.4	16.0	26	47.9	47.4	50	.997
LWC	.5−.75	358	1.8	2.3	4.2	5.6	8.2	13.7	19.3	19.5	20	.998
LWC	.75−1.0	104	.8	1.0	1.9	3.7	5.2	7.3	11.8	12.5	12	.995
LWC	>1.0	67	1.0	1.4	2.1	2.9	3.3	4.2	6.0	6.1	6	.995
−15 to −20°C		284	2.1	2.6	5.0	6.8	9.5	15.0	18.6	20.6	20	.996
−20 to −25°C		187	2.1	2.7	5.6	7.2	8.2	18.6	20.0	20.1	20	.991

*R = Correlation Coefficient

THE DETERMINATION OF THE TEMPERATURE EXTREMES.

The range of temperatures associated with the observed supercooled cloud data ranged from -0.1° C to -25° C; however, only limited amounts of NACA supercooled cloud data was found in the range of 0 to -5° C for the reasons discussed earlier. Thus, for obvious reasons, 0° C was established as the warmer limit for the temperature extreme. In establishing the colder limit for the characterization, it was decided to use only observation which occurred in the range of -20 to -25° C for the Weibull prediction, as opposed to the entire data set which covered all three temperature ranges. By so doing, the ranges of the warmer temperature ranges would be retained intact and any extreme predicted temperature resulting from the Weibull 99.9 percentiles would be included as an extension of the coldest temperature range. All data in the coldest temperature range was taken in layer clouds and encompassed some 179 data miles over 37 observation (icing events).

Using the previously established procedure, Ta was ordered as a function of data miles and then the appropriate percentiles for each 1 degree temperature interval was determined and plotted in Weibull coordinates. The Weibull 99.9 percentile value was then determined from the line of best fit established by linear regression analysis to a correlation coefficient of 0.955. The Weibull 99.9 percentile was determined to be -24.6° C and compared favorably with the coldest observed temperature of -25° C. Table 2 presents the percentiles for each of the 1° C temperature intervals and the associated number of data miles. Consequently, the colder limit for the new charaterization was established at -25° C. In retrospect, this temperature is significantly warmer than the -40° C suggested by FAR 25, appendix C.

TABLE 2. TEMPERATURE EXTREMES PERCENTILES

OBSERVED DATA				
Ta (-C)	PERCENTILES	NO. OF DATA MILES	WEIBULL 99.9% Ta	RECOMMENDED EXTREME Ta
20 to 21	38	68		
21 to 22	65.2	48.7		
22 to 23	92.0	47.9		
23 to 24	94.7	4.8		
24 to 25	97.3	4.7		
25	100.00		-24.6°C	-25°C
	TOTAL	179		

THE DETERMINATION OF LWC AND MVD EXTREMES.

Having established the three temperature ranges and the temperature extremes for the new characterization, and realizing that a presentation comparable to that employed in the FAR 25, appendix C, criteria would be readily interpretable by versed users, a prudent approach dictated that a separate envelope of LWC versus MVD for each of the temperature ranges be developed. Each envelope would exclude those values of LWC and MVD in which the exceedance probability was less than 1 part in a 1,000; i.e., greater than the Weibull determined 99.9 percentiles. To this effect, the data set for each temperature range was subdivided into subset for each 5 μm increment of MVD. It was assumed that the data within each 5 μm increment followed the same distribution laws as the complete data set within the same temperature range of interest. The validity of this assumption would be borne out by the value of the goodness of fit correlation coefficient (R).

The resulting subset were then ordered, and the percentiles corresponding to each tenth of a gm^{-3} of LWC were determined as a function of data miles and then plotted in Weibull coordinates in a manner analogous to that employed in the prediction of the Weibull 99.9 percentiles for extreme Ta and maximum horizontal extents. Once determined, the Weibull 99.9 percentile values for LWC for each of the 5 μm increments were used to establish the maximum outline for each of the temperature ranges.

For those cases in which a straight line fit could not be obtained with a high correlation coefficient, a value consistent with establishing a smooth curve between adjacent points was faired dn. Also, data points were faired in for the intervals between 40 to 45 μm, and 22 to 28 μm in the mid-temperature range where there were no observed data. A tabulation of these parameters is included in appendix E. In a similar manner, it was attempted to apply the same procedure to the establishment of the lateral limits of MVD in each temperature range, in selected increments of LWC. Results of this procedure were inconclusive typically yielding minimum values of 1 to 2 μm and maximum values of 40 to 50 μm with corresponding poor correlation coefficient throughout the range of LWC's for both of the warmer temperature ranges. Similar unfavorable results were obtained with the Gumbel distribution. Consequently, observed values were used to establish the lateral extremes of the icing envelopes, except at the .04 gm^{-3} points which were arbitrarily selected as a minimum value to accommodate supercooled fog. Points in the region of 0.1 to .04 gm^{-3} were typically faired in with the dominating factor being a smooth continuation of the envelope to the .04 gm^{-3} LWC level.

The graph of figure 4 shows the three envelopes of LWC versus MVD resulting from this process in which:

M = observed extreme data points.

W = Weibull 99.9 percentiles data points.

f = Faired data points.

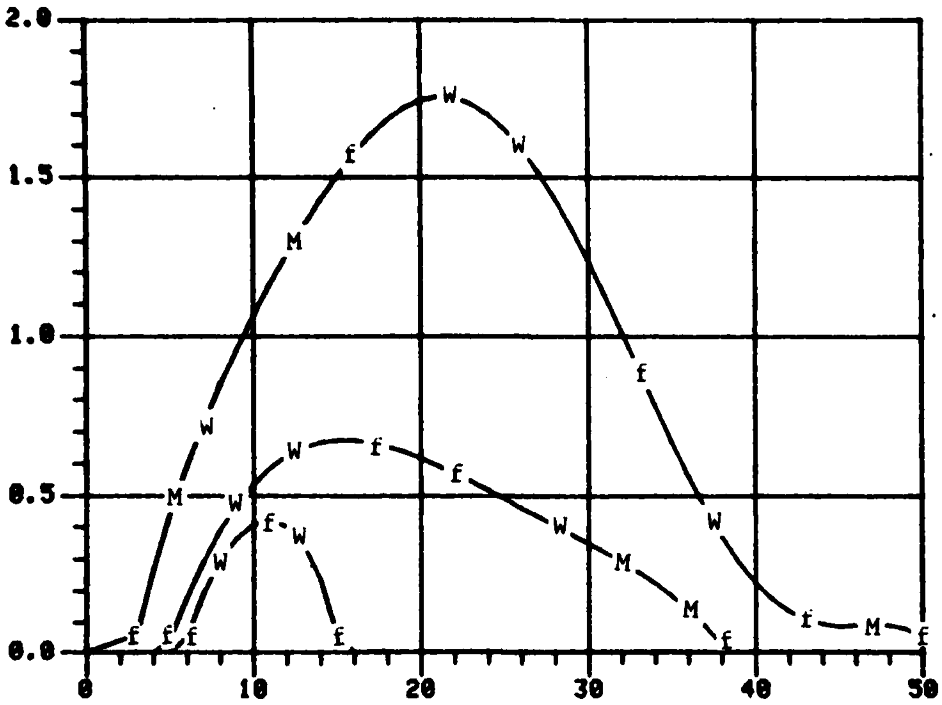


FIGURE 4. THE CHARACTERIZATION DEPICTING MEASURED, WEIBULL PREDICTED AND FAIRED-IN EXTREME VALUES

MVD VERSUS TEMPERATURE.

An interesting characteristics exhibited by the new characterization data of figure 5 is the independence/dependence of MVD on temperature. In the 0 to -15° C temperature range, MVD appears independent of temperature and occurred in most droplets diameters from 3 to 50 µm. Possibly these MVD's would have approached .01 µm had it not been for the typical lower limit of 3 µm used in most of the PMS probe measurements and the 5 µm MED lower limits imposed by the RMC measurement techniques (NACA TR 1215, reference 6). However, in the temperature range of -15 to -20° C, and in the range of -20 to -25° C, the median MVD tended toward the smaller sizes with centers and/or peaks around 10 to 14 µm. Also, in these ranges, the MVD extremes changed from 3 and 50 µm for the warmer temperature range to 5 and 38 µm for the mid-temperature range and to 7 and 15 µm in the coldest temperature range.

This characteristic, found in the original NACA data and supported by the modern data, is not exhibited in FAR 25, appendix C, due to the critical droplet concept as defined in NACA TN 1472. The critical diameter, as explained, is the smallest diameter of droplet size that will impinge on a given element. Thus, droplets sized less than critical could be ignored as noncontributory to ice accretion. For the large wing and windshield ice protection systems under evaluation during the late 1940's, 15 µm was determined to be the critical diameter for droplet size.

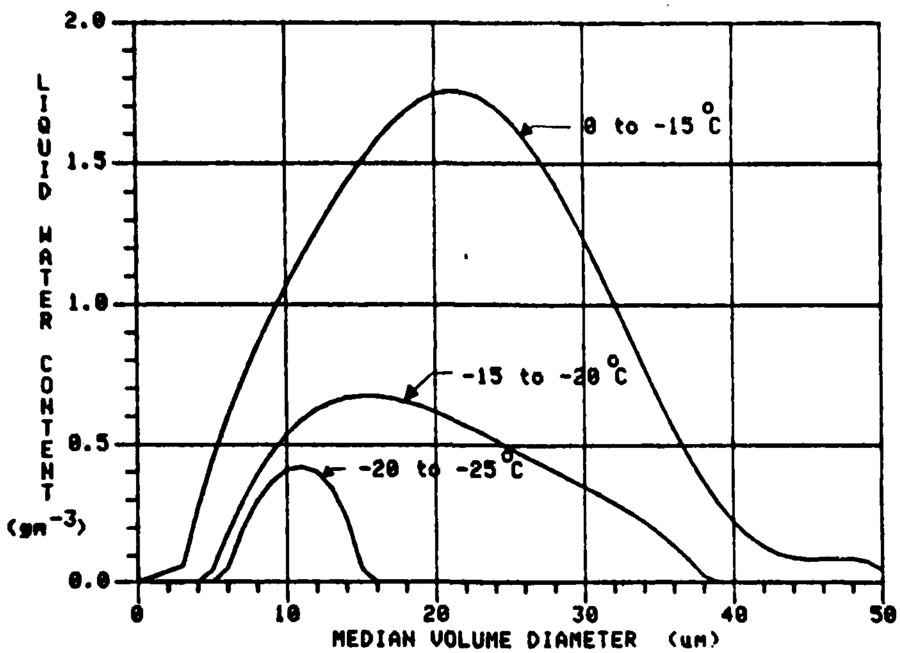


FIGURE 5. THE CHARACTERIZATION DEPICTING THE SHIFT IN MVD WITH TEMPERATURE

VERTICAL LIMITS OF THE NEW CHARACTERIZATION.

The new characterization of supercooled clouds has been generated from data gathered in icing clouds over the conterminous United States (U.S.) and nearby offshore areas from near ground level to 10,000 feet AGL. Of the 6,700+ data miles, approximately 10 percent (662 miles) were obtained between 10,000 feet and 14,000 feet MSL and encompassed 159 icing events. Obviously, these observations were obtained over elevated and/or mountainous terrain which extended up to 4000 feet or higher. A review of U.S. weather records indicates that the prevailing MSL pressures in the vicinity of the areas where the NACA observation were taken varied from a low of 29.77 inches of mercury (inHg) to a high of 30.12 inHg. with 29.9 inches being typical. Thus, those observations whose altitudes were not referenced to pressure altitude (PA) could readily be converted to PA without paying undue penalties for inaccuracy. At worst, these inaccuracies would be on the order of 200 to 300 feet (a tolerable value).

The data base of reference 3 also includes 15 icing events representing some 61 data miles of observations which were taken between 14,200 and 15,200 feet PA. These data, taken over elevated terrain were not included in the analysis because the AGL altitude could not accurately be determined to within ±500 feet, even though the prevailing altitudes were less than 10,000 feet AGL. Typical areas encompassed by these observations include: Flagstaff, Arizona and vicinity; northwestern New Mexico to northern Arizona to southern Nevada; western Idaho to eastern Montana; etc. In all cases, the maximum observed values of LWC, Ta, and MED/MVD for these pressure altitudes were well within the limits established by the new characterization. The maximum observed values of LWC, MED/MVD, and Ta for this altitude range were 0.85 gm^{-3}, 31 μ m, and -21° C, respectively. All of these maximum observations occurred within 10,000 feet of the terrain and were associated with different icing events and encompassed both modern and historic data. Therefore, it is concluded that the new characterization of supercooled clouds can accommodate altitudes up to 15,000 feet PA over evlevated terrain, provided the clouds are within 10,000 feet of the surface. Thus, the verical limit of the new characterization of supercooled clouds is established at 10,000 feet AGL or 15,000 feet PA, whichever is lower.

THE LWC ADJUSTMENT FACTOR.

Although FAR 25, appendix C, presents LWC adjustment factor curves that are predicated upon cloud horizontal extent, for both the intermittent maximum and continuous maximum conditions, the new characterization does not do so. These LWC adjustment factor curves, as developed by NACA and documented in TN 2738 (reference 4) were intended to accommodate design values of LWC whenever the selected horizontal extent differed from the standard distance of 3 statue miles for convective clouds or 20 statute miles for layer clouds. These distances were regarded as standard by NACA, since the majority of their RMC measurements were averaged over 3 statute miles in convective clouds and 10 statute miles in layer clouds. The analysis of TN 2738 subsequently recommended a standard distance of 20 statute miles for design purposes for layer clouds.

The existence of the LWC adjustment factor curves in FAR 25, appendix C, has promoted some misconceptions as to their useage. The original intent was to aid in the selection of probable LWC design values that would represent averaged values during exposure over varying distances. These curves were based on the observed fact that averaged LWC values decreased with increasig distances.

As an example: When employing the continuous maximum LWC adjustment factor curves of FAR 25, appendix C, (see page A-4 of appendix A), an aircraft component or system designed to accommodate a continuous maximum condition of say 0.5 gm^{-3} LWC for an icing cloud horizontal extent of 45 nmi would have the LWC design value of 0.5 gm^{-3} reduced by a factor of 0.7 to 0.35 gm^{-3} since the design value of horizontal extent differs from the standard. In a similar manner, for a design value of cloud horizontal extent of 9 nmi, the LWC value would be increased by a factor of 1.2 to 0.6 gm^{-3}.

Unfortunately, in time, the LWC adjustment factor curves also found use in certification flight testing, whereby failure to find a desired LWC value in nature was compensated for by increasing the flight distance. The merits of this latter usage is beyond the scope of this report, other than to state that such usage is not the original intent.

The new characterization is based upon the individual icing event whose durations, especially for the modern observations, did not have a standard distance and, in fact, were continued until one of the rules for defining an icing event (appendix B) were met. Horizontal extents were then determined from these individual icing events, such that their exceedance probability would be less than one part in a thousand. The new characterization presents the specific horizontal extents in terms of durations in nautical mile for each range of LWC values encompassed by the three temperature ranges. Thus, alleviating the need for an adjustment factor which is predicated upon a deviation from a standard cloud horizontal extent.

SUFFICIENCY OF THE DATA BASE.

The new characterization has been generated from data representing some 6,700 miles of aerial observations in winter and early spring synoptic conditions over the conterminous United States, Great Lakes, and nearby offshore areas. These data include approximately equal amounts of modern and historical observation and encompass all flyable major weather categories and airmass categories conducive to aircraft icing in supercooled clouds. Table B-1 of reference 3 further details these observations in terms of NACA data and modern data and presents percentages of required data versus observed data, which are based upon maximum values of LWC observed for each synoptic condition. Although this table presents a case for some additional observations in warm, cold, and occluded fronts; deep cyclonic storms; and in lake effect, orographic and low ceiling clouds; this need if compensated for in the new characterization. It would be a shortcoming had the new criteria been based strictly upon observations and employed no extreme value prediction technique in their establishment. However, such was not the case in the generation of the new characterization since least squares logarithmic regression estimation technique based upon the Weibull distribution was employed to predict the extreme values of the supercooled cloud properties to an exceedance probability level of 0.001.

It is the author's opinion that although additional observations would enhance the data base, these data would not affect the maximum values obtained by the analysis process for the four key parameters of the new characterization; i.e., LWC, Ta, MVD, and duration. It should be pointed out that the maximum observed value of LWC (1.7 gm^{-3}) was found in Pacific coast orographic/cumulus clouds and the most probable synoptic condition for exceeding this value would also occur in Pacific coast orographic conditions.

THE NEW CHARACTERIZATION - IN RETROSPECT.

The new characterization combines the four key paameters for supercooled clouds; i.e., LWC, Ta, MVD and duration, into a single depiction/chart that encompasses both layer and convective clouds. In retrospect, FAR 25, appendix C, presents essentially the same type of information in six different charts and graphs. Figure 6 presents a chart showing LWC, Ta, and MVD values of the new characterization superimposed over both the FAR 25, appendix C, intermittent maximum and continuous maximum criteria. On this chart, all temperatures have been converted to celsius and the -40° F temperature contour line of the intermittent maximum criteria has been omitted, primarily for clarity. Some of the readily apparent observations/conclusions that can be drawn from this chart are:

1. The new characterization encompases MVD's between 3 μm and 15 μm that were omitted from the FAR 25, appendix C, criteria.

2. The new characterization presents a maximum LWC value of 1.74 gm^{-3} at 22 μm, whereas the FAR 25, appendix C, criteria depicts a maximum value of 2.9 gm^{-3} at 15 μm. It should be noted that this value (2.9 gm^{-3}) is deemed excessively conservative for altitudes below 10,000 feet AGL.

3. The new characterization depicts no temperature colder than -25° C, whereas the FAR 25, appendix C, criteria presents temperatures as cold as -30° C and suggests temperatures as cold as -40° F.

4. In the intermittent maximum criteria of FAR 25, appendix C, all values of LWC associated with MVD's larger than 28 μm significantly exceeds those of the new characterization and are deemed excessively conservative for altitudes below 10,000 feet AGL.

5. All values of LWC and MVD for the continuous maximum criteria of FAR 25, appendix C, fall well within the coverage of the new characterization.

6. Nearly all values of LWC and their associated temperature range for the intermittent maximum criteria of FAR 25, appendix C, are excessively conservative in comparison to the new characterization.

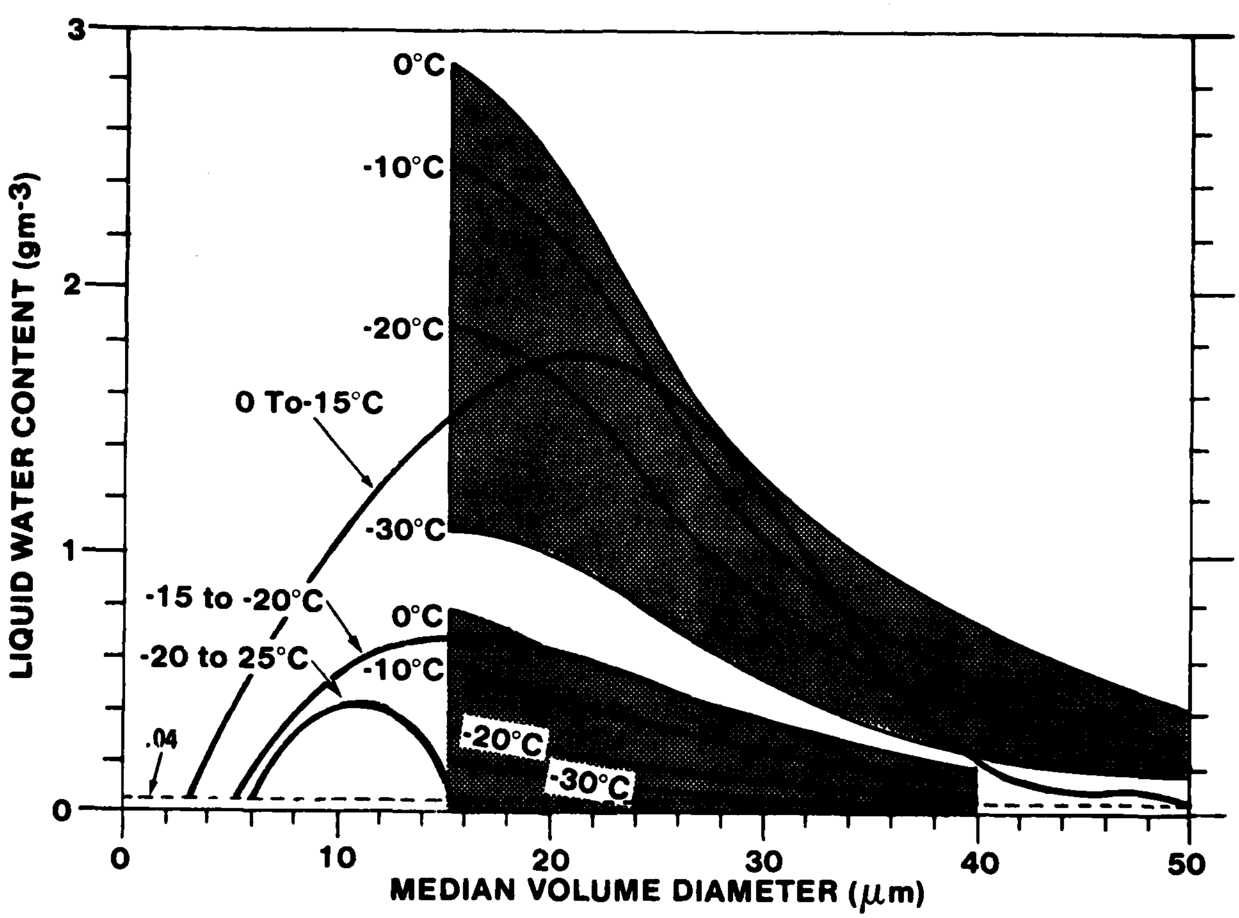


FIGURE 6. THE NEW CHARACTERIZATION SUPERIMPOSED ON THE FAR 25 APPENDIX C, INTERMITTENT MAXIMUM AND CONTINUOUS MAXIMUM CRITERIA

At this point in the report, it is deemed prudent to present several comments relative to the techniques employed in the generation of the FAR 25, appendix C, criteria and in the generation of the new characterization, so as to emphasize that there has been no reduction in the level of safety, even though the techniques are different.

1. The NACA report, TN 1855 (reference 5), formed the basis for the establishment of the values of LWC, Ta, and MVD for the FAR 25, appendix C criteria. These values were based upon the experience and judgment of the experimenters at that point in time and employed no statistical analysis in their derivation.

2. The NACA report, TN 2738 (reference 4), established the basis for the horizontal extent and the LWC correction factor. Also in its analysis, it showed that in some instances values of LWC as delineated in TN 1855, could be shown to have a probability of exceedance (Pe) of about .001. However, in several instances the same analysis presented required values of LWC (commensurate with a probability of exceedance of 0.001) that were larger than those of TN 1855 (this implies a Pe > 0.001). In contrast, values of LWC of the new characterization were determined so that their probability of exceedance was 0.001 or less.

3. The analysis of TN 2738 employed only two points to generte the regression line in Gumbel coordinates, whereas, the analysis of this report employed at least twice as many points to establish the regression line in Weibull coordinates. Also, the analysis of this report employed a correlation coefficient (R) to test the goodness of fit of the regression line and rejected those predicted extreme values whose R was not sufficiently high.

A MATHEMATICAL DESCRIPTION OF THE ENVELOPES.

Having established the new characterization envelopes for each of the three temperature ranges, it was deemed prudent to provide a means of consistently obtaining these characterizations without resorting to tables. Such a means would facilitate engineering design calculations when performed by computer at a later date. To this effect, algebraic polynomial equations which describe each icing envelope within its range of MVD and °C were generated using a FORTRAN computer program based upon orthogonal projections. These equations take the form:

$$f\,(X_i) = C(0) + C(1)X_i^1 + C(2)X_i^2 \ldots C(n)X_i^n$$

where $f\,(X_i)$ = the value of LWC corresponding to the i th MVD

C ( ) = coefficients of the polynominal equations.

This resulted in a 7th degree equation for the warmer temperature range of 0 to -15° C, a 5th degree equation for the mid-temperature range, and a 4th degree equation for the coldest temperature range. Table 3 presents the values of LWC determined by the polynomial equation. These values follow closely the Weibull 99.9 percentile or faired values, and in no case varied more than .03 gm^{-3}. The coefficients for each of the polynomial equations is listed in table 4.

To facilitate the graphical reproduction of these envelopes by computer, appendix F includes a FORTRAN computer program that possibly can be employed without modifications. This program is compatible with the Tektronix 4000 series of graphic terminal which can accommodate the "PLOT-10" routines in conjunction with a main frame computer.

TABLE 3. VALUES OF LWC AND MVD

	LIQUID WATER CONTENT (gm^{-3})				LIQUID WATER CONTENT	
MVD - um	0 TO -15°C	-15°C TO -20°C	-20°C TO -25°C	MVD - um	0 TO -15°C	-15°C TO -20°C
	LWC	LWC	LWC		LWC	LWC
3	.04			26	1.58	.46
4	.26			27	1.50	.44
5	.44	.04		28	1.42	.41
6	.60	.18	.04	29	1.32	.38
7	.73	.30	.20	30	1.22	.35
8	.85	.39	.30	31	1.11	.32
9	.96	.47	.36	32	.99	.29
10	1.06	.53	.40	33	.87	.26
11	1.16	.58	.41	34	.76	.22
12	1.25	.62	.40	35	.64	.18
13	1.34	.64	.34	36	.53	.14
14	1.42	.65	.23	37	.44	.09
15	1.49	.66	.04	38	.35	.04
16	1.56	.66		39	.27	
17	1.62	.65		40	.21	
18	1.67	.64		41	.16	
19	1.70	.63		42	.13	
20	1.73	.61		43	.11	
21	1.74	.59		44	.10	
22	1.74	.57		45	.10	
23	1.73	.54		46	.11	
24	1.69	.52		47	.11	
25	1.64	.49		48	.11	
				49	.09	
				50	.04	

TABLE 4. COEFICIENTS OF THE POLYNOMIALS FOR CALCULATION OF LWC AND MVD

COEFFICIENTS	TEMPERATURES AND MVD'S		
	MVD: 3 to 50 um Ta: 0 to -15°C	MVD: 5 to 38 um Ta: -15 to -20°C	MVD: 6 to 15 um Ta: -20 to -25°C
C(0)	-9.1394344E-01	-1.0522805E-00	-3.5238374E-00
C(1)	4.3085546E-01	2.9960598E-01	1.2561859E-00
C(2)	-4.5292582E-02	-1.8312112E-02	-1.6156104E-01
C(3)	3.2568176E-03	4.6770813E-04	1.0077214E-02
C(4)	-1.2806039E-04	-4.7589022E-06	-2.5568181E-04
C(5)	2.4167480E-06	5.0893099E-09	
C(6)	-1.8602906E-08		
C(7)	2.7335108E-11		

CONCLUSIONS

The graph of figure 7 depicts the final characterization of the atmosphere for supercooled clouds from ground level to 10,000 feet AGL or 15,000 feet PA whichever is lower. The envelope of each of the temperature ranges encompass values with a probability of exceedance greater than one part in a thousand. Values which fall outside of these icing envelopes would probably be encountered less than one time in each 1,000 icing event encounters. A fundamental difference between this new characterizations and FAR 25, appendix C, is the intent of each. FAR 25, appendix C, was developed as a criteria to facilitate the design of ice protection systems and equipment primarily for transport category aircraft of the early 1950 time-frame. The new characterization, as the name implies, is a characterization of supercooled clouds between ground level and 10,000 feet AGL. As such, it inherently has parameters which may be employed in subsequent design of ice protection systems and equipments for aircraft which operate between ground level and 10,000 feet AGL. However, in its present form, it should be treated as a characterization and not as a final design criteria.

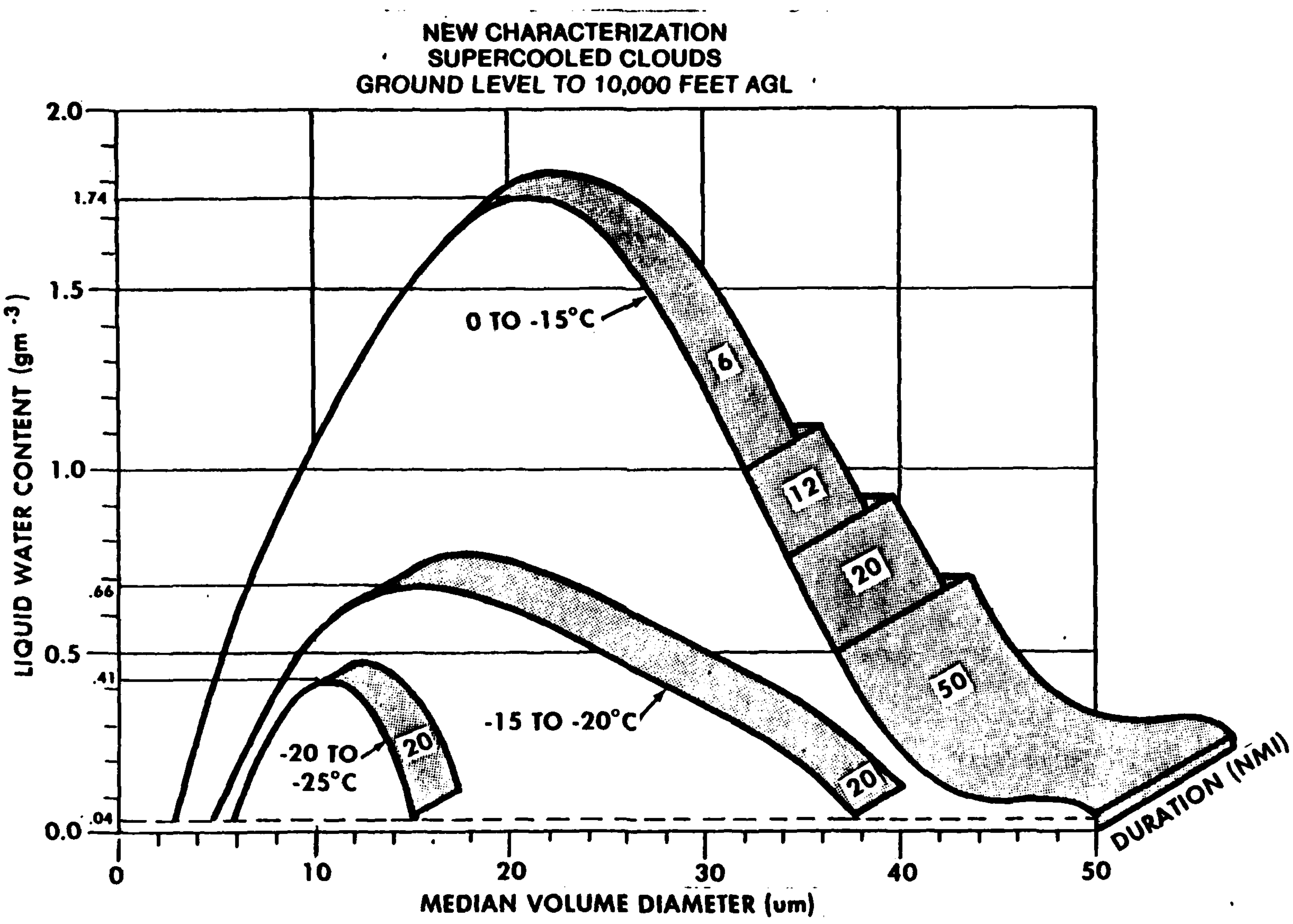


FIGURE 7. A FINAL DEPICTION OF THE NEW CHARACTERIZATION OF SUPERCOOLED CLOUDS FROM GROUND LEVEL TO 10,000 FEET AGL

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APPENDIX A

ATMOSPHERIC ICING CRITERIA FAR 25, APPENDIX C

Appendix C

(a) *Continuous maximum icing.* The maximum continuous intensity of atmospheric icing conditions (continuous maximum icing) is defined by the variables of the cloud liquid water content, the mean effective diameter of the cloud droplets, the ambient air temperature, and the interrelationship of these three variables as shown in Figure 1 of this Appendix. The limiting icing envelope in terms of altitude and temperature is given in Figure 2 of this Appendix. The inter-relationship of cloud liquid water content with drop diameter and altitude is determined from Figures 1 and 2. The cloud liquid water content for continuous maximum icing conditions of a horizontal extent, other than 17.4 nautical miles, is determined by the value of liquid water content of Figure 1, multiplied by the appropriate factor from Figure 3 of this Appendix.

(b) *Intermittent maximum icing.* The intermittent maximum intensity of atmospheric icing conditions (intermittent maximum icing) is defined by the variables of the cloud liquid water content, the mean effective diameter of the cloud droplets, the ambient air temperature, and the inter-relationship of these three variables as shown in Figure 4 of this Appendix. The limiting icing envelope in terms of altitude and temperature is given in Figure 5 of this Appendix. The inter-relationship of cloud liquid water content with drop diameter and altitude is determined from Figures 4 and 5. The cloud liquid water content for intermittent maximum icing conditions of a horizontal extent, other than 2.6 nautical miles, is determined by the value of cloud liquid water content of Figure 4 multiplied by the appropriate factor in Figure 6 of this Appendix.

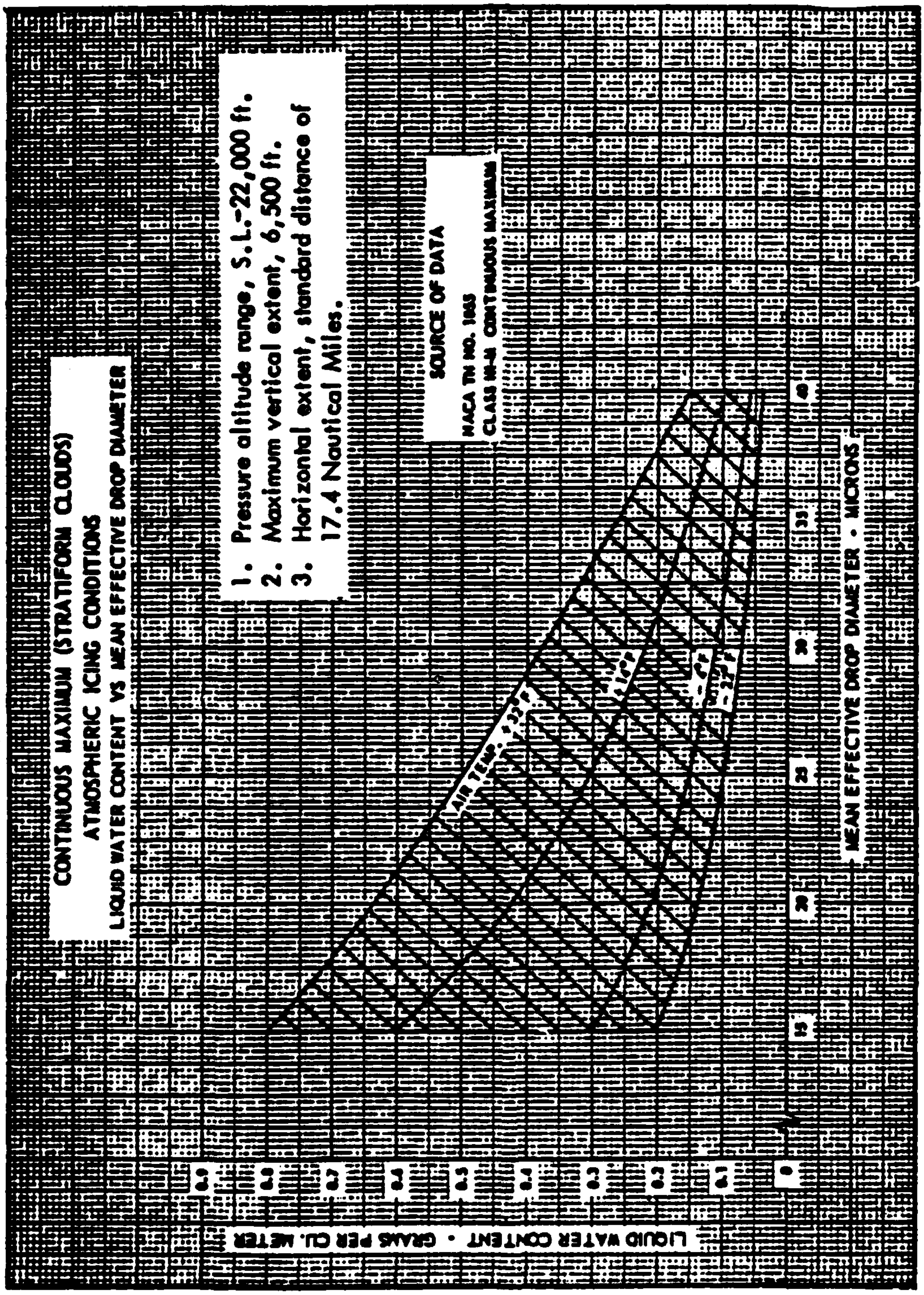
CONTINUOUS MAXIMUM (STRATIFORM CLOUDS)
ATMOSPHERIC ICING CONDITIONS
LIQUID WATER CONTENT VS MEAN EFFECTIVE DROP DIAMETER
1. Pressure altitude range, S.L.-22,000 ft.
2. Maximum vertical extent, 6,500 ft.
3. Horizontal extent, standard distance of 17.4 Nautical Miles.
SOURCE OF DATA
NACA TN NO. 1855
CLASS III-M CONTINUOUS MAXIMUM
AIR TEMP. +32°F
LIQUID WATER CONTENT - GRAMS PER CU. METER
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
MEAN EFFECTIVE DROP DIAMETER - MICRONS
15
20
25
30
35
40

FIGURE 1.

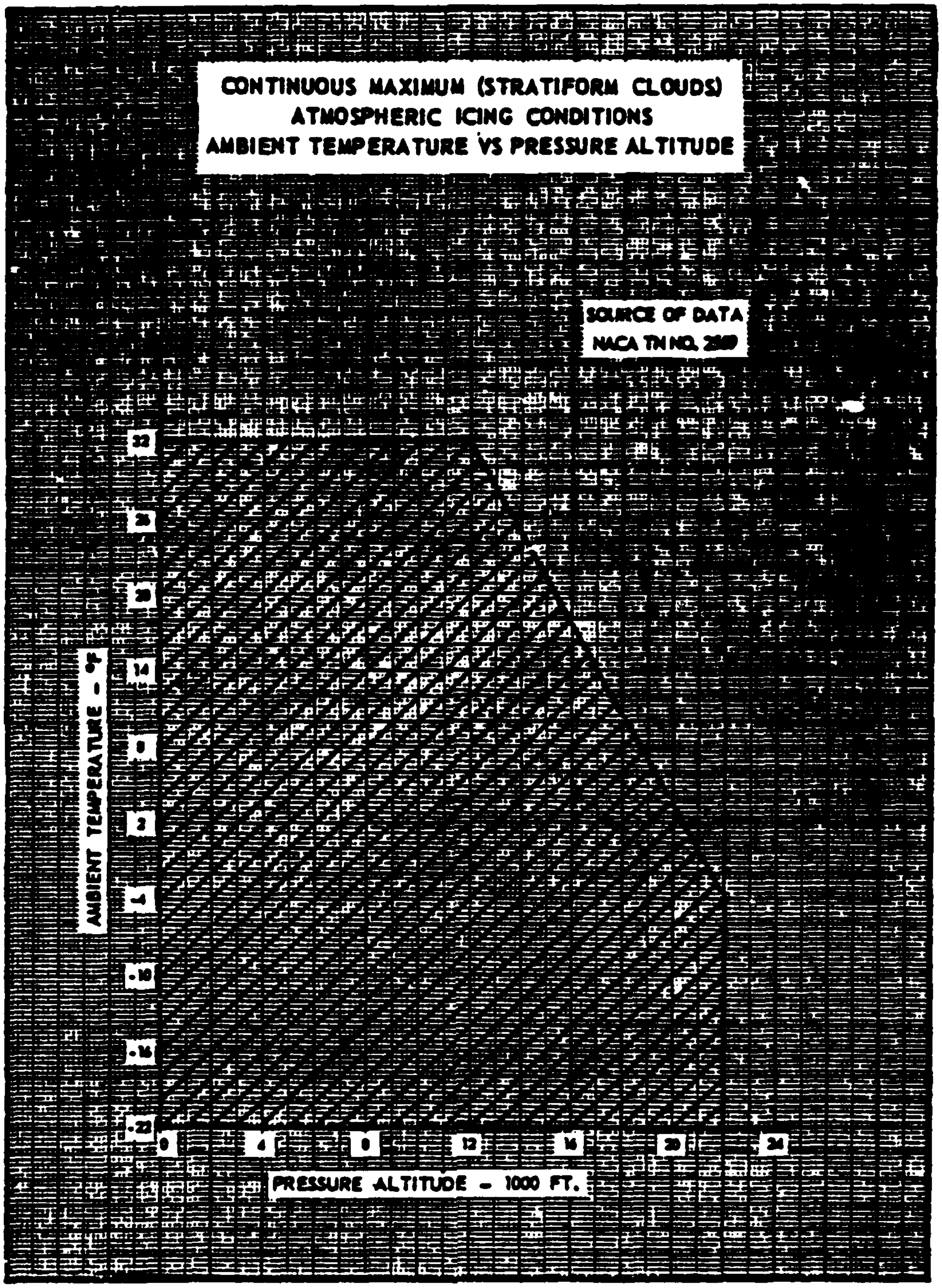

FIGURE 2.

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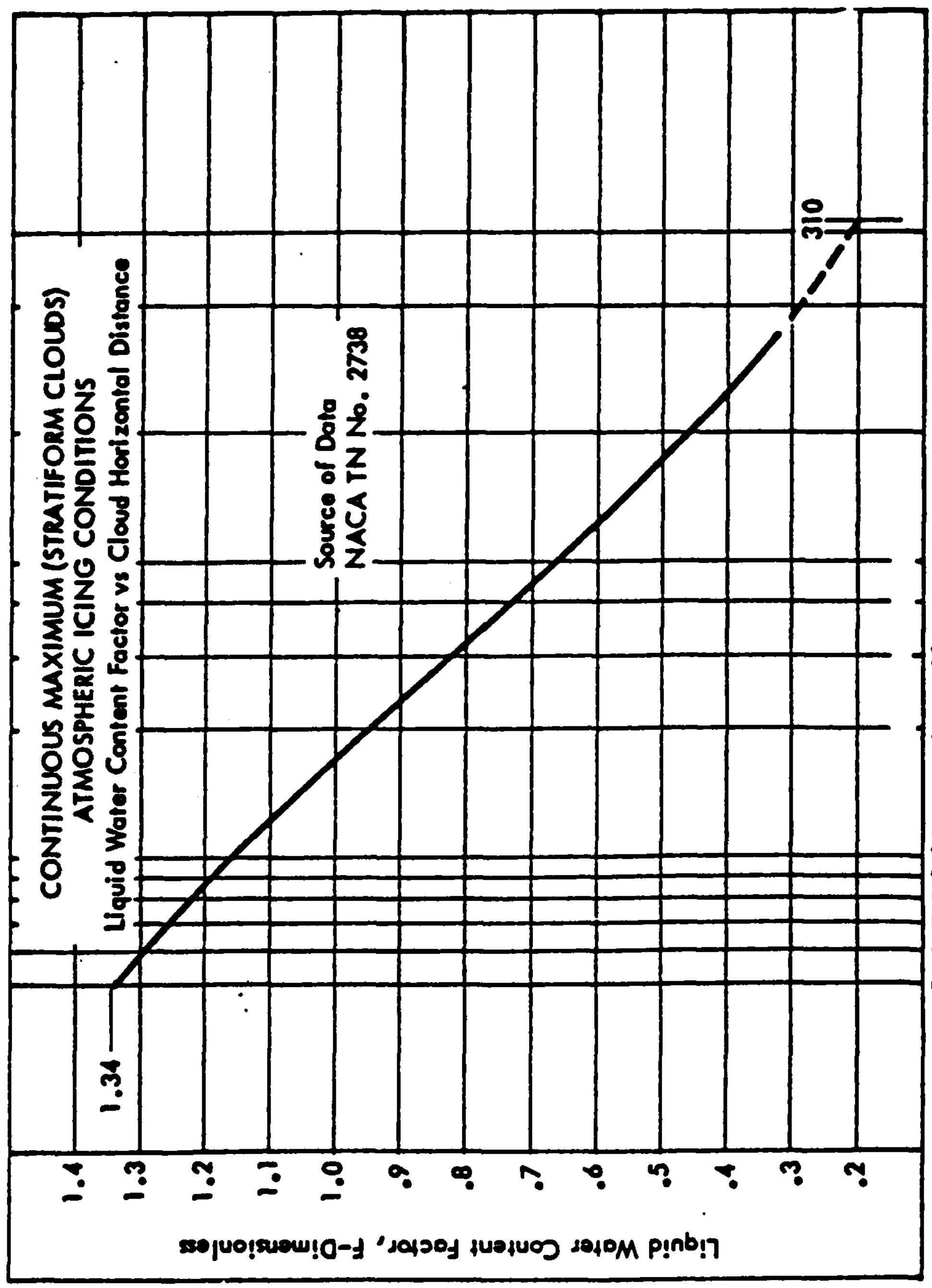

CONTINUOUS MAXIMUM (STRATIFORM CLOUDS)
ATMOSPHERIC ICING CONDITIONS
Liquid Water Content Factor vs Cloud Horizontal Distance
Source of Data
NACA TN No. 2738
1.34
310
Liquid Water Content Factor, F-Dimensionless
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
5 6 7 8 9 10
20
30
40
50
100
200
300
CLOUD HORIZONTAL EXTENT - NAUTICAL MILES

FIGURE 8.

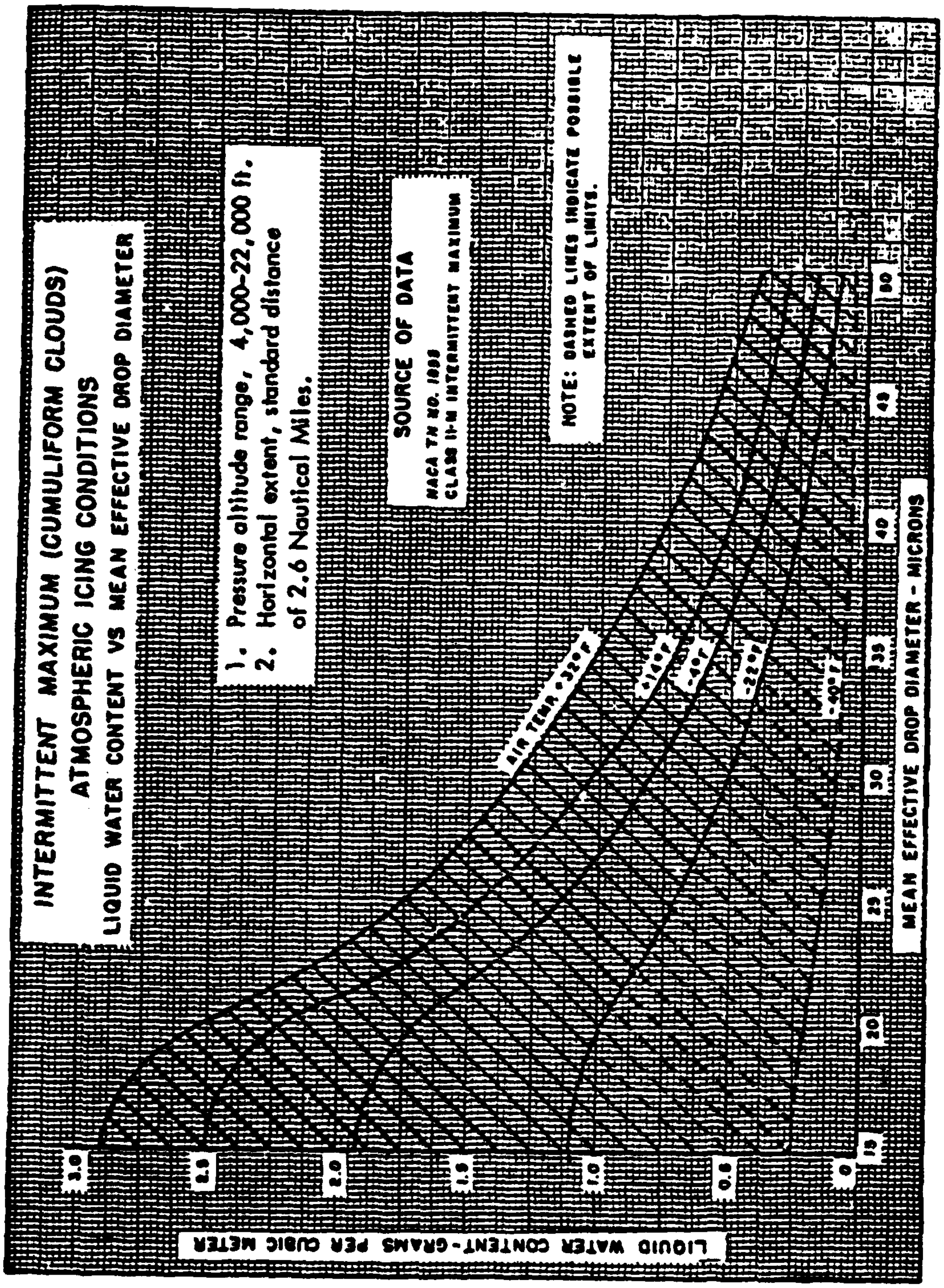
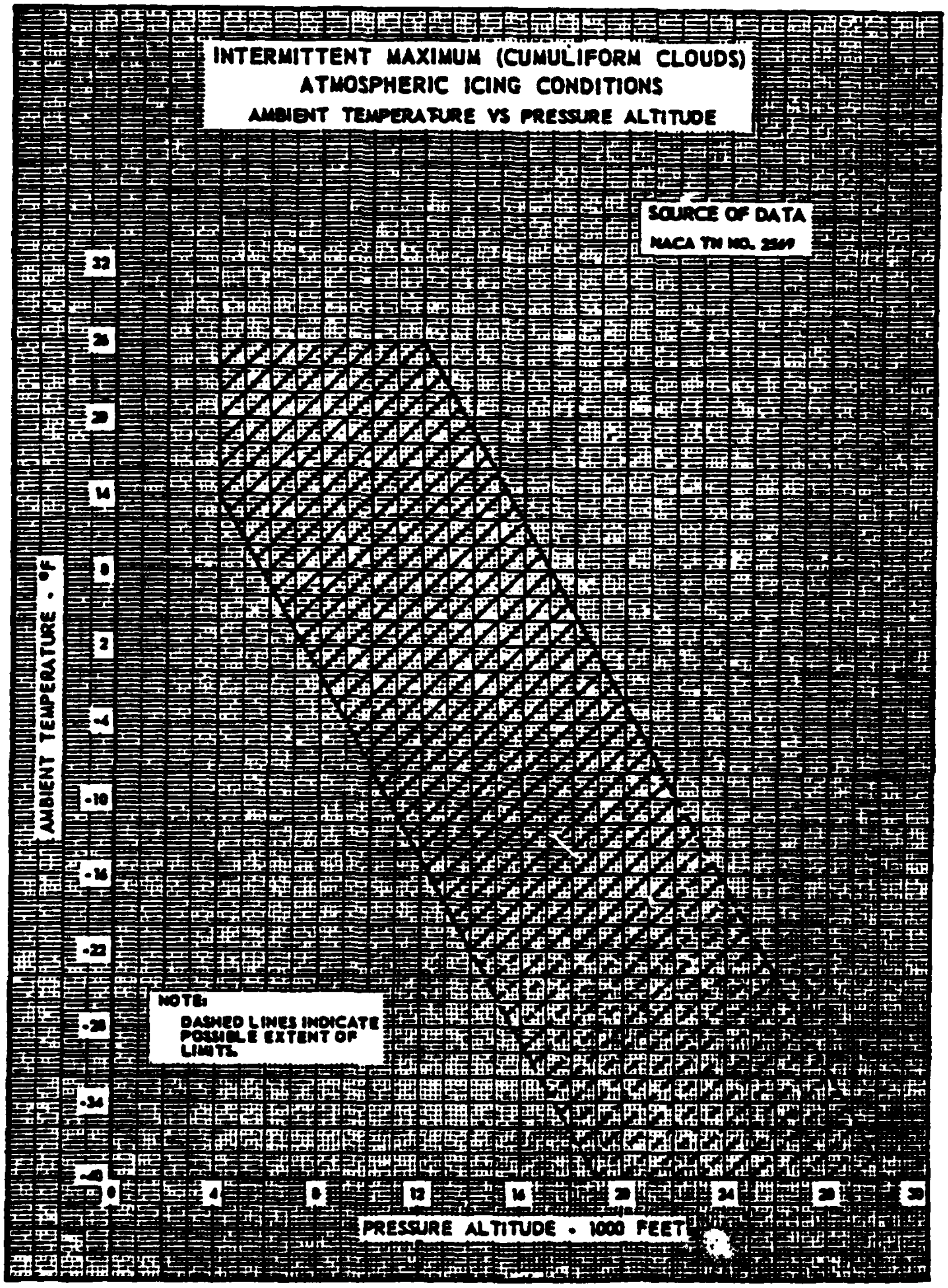

INTERMITTENT MAXIMUM (CUMULIFORM CLOUDS)
ATMOSPHERIC ICING CONDITIONS
LIQUID WATER CONTENT VS MEAN EFFECTIVE DROP DIAMETER
1. Pressure altitude range, 4,000-22,000 ft.
2. Horizontal extent, standard distance of 2.6 Nautical Miles.
SOURCE OF DATA
NACA TN NO. 1855
CLASS II-M INTERMITTENT MAXIMUM
NOTE: DASHED LINES INDICATE POSSIBLE EXTENT OF LIMITS.
AIR TEMP. +32°F
+14°F
-4°F
-22°F
-40°F
LIQUID WATER CONTENT-GRAMS PER CUBIC METER
3.0
2.5
2.0
1.5
1.0
0.5
0
15
20
25
30
35
40
45
50
MEAN EFFECTIVE DROP DIAMETER - MICRONS

FIGURE 4.



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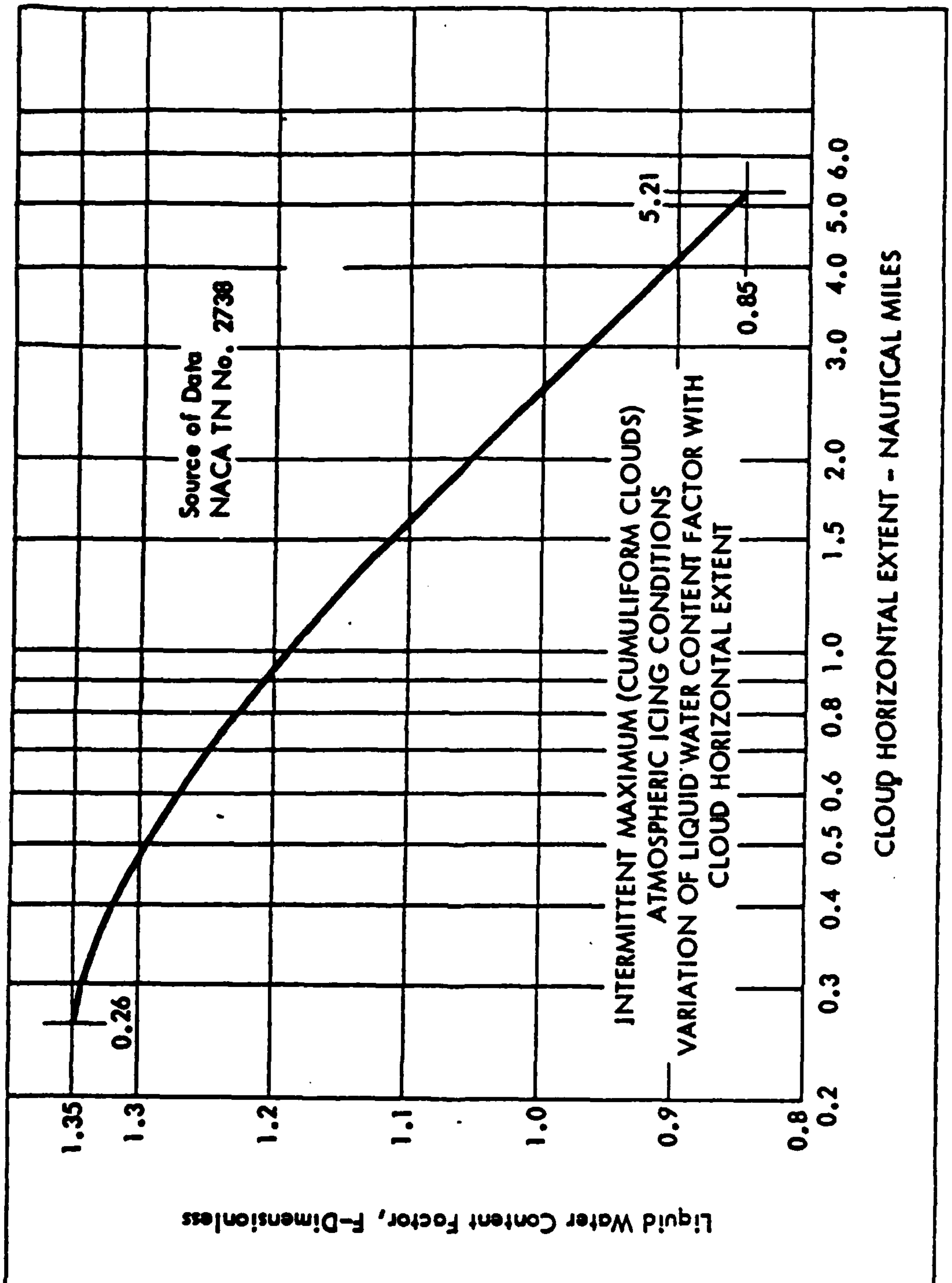

INTERMITTENT MAXIMUM (CUMULIFORM CLOUDS)
ATMOSPHERIC ICING CONDITIONS
VARIATION OF LIQUID WATER CONTENT FACTOR WITH
CLOUD HORIZONTAL EXTENT
Source of Data
NACA TN No. 2738
Liquid Water Content Factor, F-Dimensionless
CLOUD HORIZONTAL EXTENT - NAUTICAL MILES
1.35
1.3
1.2
1.1
1.0
0.9
0.8
0.2
0.3
0.4
0.5
0.6
0.8
1.0
1.5
2.0
3.0
4.0
5.0
6.0
0.26
0.85
5.21

Figure 6.

APPENDIX B

CLOUD PROPERTY LIMITS AND RULES FOR DEFINING ICING EVENTS*

1. Level Flight Through Continuous Cloud or Cloud Parcels about 1 nm or more wide.

RULES: LWC and other variables to be averaged over flight path in cloud until:

A - Aircraft exits main cloud,

B - Outside air temperture changes by $\pm 1.5°C$,

C - Outside air temperature rises above 0° C,

D - Droplet Median Volume Diameter changes by ± 2 1/2 μm,

E - Aircraft changes flight level by ± 500 feet (± 150 meters),

F - Icing rate changes by $\pm 50\%$

G - Droplet concentration, N, changes by $\pm 50\%$ or ± 200, whichever is least,

H - Measurement arbitrarily terminated,

J - Aircraft exits continuous cloud parcel,

K - Subsequent cloud droplet probe data invalidated by snow or ice part icles in cloud.

2. Vertical Profiles in Continuous Cloud

RULE: Report representative values of cloud variables for every 500 feet (150 m) change in altitude.

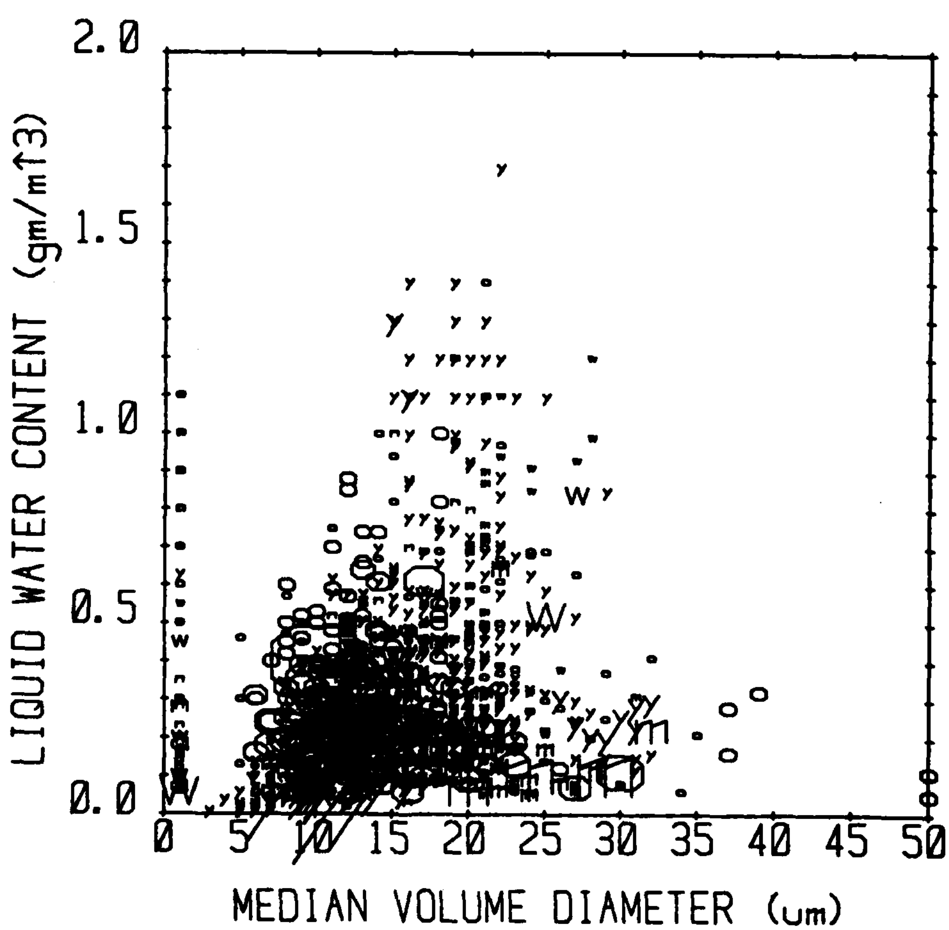
*(Op. Cit. reference 3)

APPENDIX C

SCATTER PLOTS OF "ICING EVENTS" EMPLOYED IN THE ANALYSIS

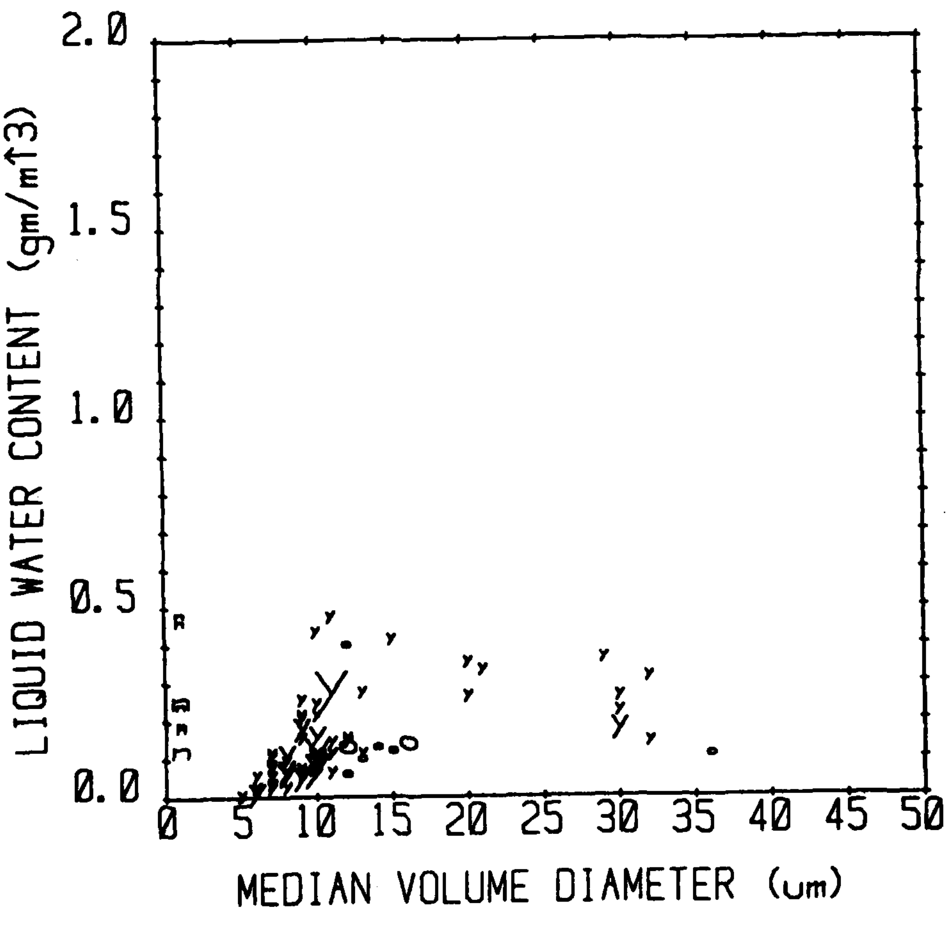
01/19/83
Using Program Tape 103-A, TrkO, File 21
Total Data Miles this Plot: 5739
Total Events this Plot: 1189
Using DATA BASE Files 1-44
Legend: m - MRI DATA
y - U. WYO. DATA
n - NRL DATA
w - U. WASH. DATA
■ - USAF/AFGL DATA
o - NACA DATA, 1946-1950
Uses Entire CONUS Data Base: NACA DATA, 1946-1950 and MODERN DATA
ALL SUPERCOOLED CLOUD TYPES
0 - 10000Ft. A.G.L.
Temp Range -15.0<T<= 0.0deg C
NACA Data in Snow not Included

m= 0- 5nmi, m = 20- 25nmi, m = 40- 45nmi,



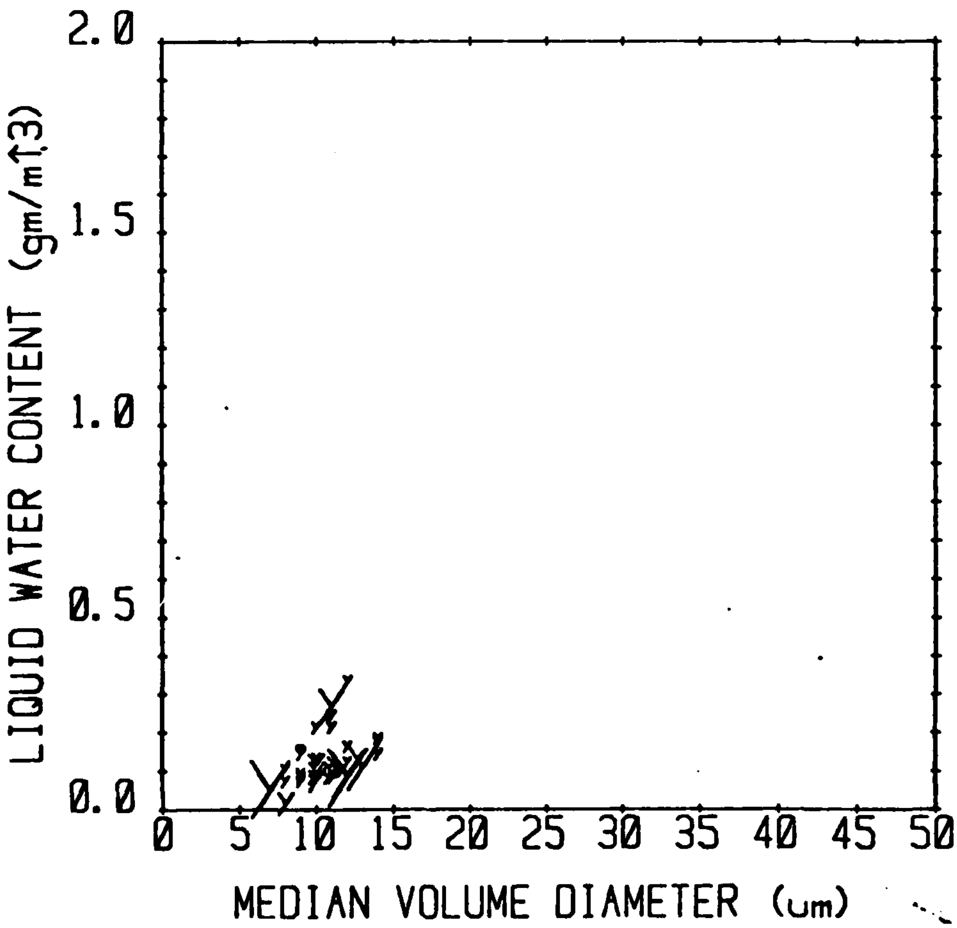
01/19/83
Using Program Tape 103-A, frk0, File 21
Total Data Miles this Plot: 259
Total Events this Plot: 78
Using DATA BASE Files 1-44
Legend: m - MRI DATA
y - U. WYO. DATA
n - NRL DATA
w - U. WASH. DATA
a - USAF/AFGL DATA
o - NACA DATA, 1946-1950
Uses Entire CONUS Data Base: NACA DATA, 1946-1950 and MODERN DATA
ALL SUPERCOOLED CLOUD TYPES
0 - 10000Ft. A.G.L.
Temp Range -20.0<T<=-15.0deg C
NACA Data in Snow not Included

m = 0- 5nmi, m = 20- 25nmi, m = 40- 45nmi,



01/18/83
Using Program Tape 103, Trk1, File 16
Total Data Miles this Plot: 187
Total Events this Plot: 37
Using DATA BASE Files 1-44
Legend: m - MRI DATA
y - U. WYO. DATA
n - NRL DATA
w - U. WASH. DATA
a - USAF/AFGL DATA
o - NACA DATA, 1946-1950
Uses Entire CONUS Data Base: NACA DATA, 1946-1950 and MODERN DATA
ALL SUPERCOOLED CLOUD TYPES
0 - 10000Ft. A.G.L.
Temp Range -30.0<T<=-20.0deg C
NACA Data in Snow not Included

m = 0- 5nmi, m = 20- 25nmi, m = 40- 45nmi,



APPENDIX D

THE WEIBULL VARIABLES

In the approach taken in these analyses, it was not necessary to determine the values of α (the scaling factor) and B (the shape parameter) of the classical Weibull distribution function given by

$$f_w(x) = 1-e^{-\alpha (x-\mu)^B} \qquad (1\text{-}C)$$

Use of the scaling factor at any value other than 1 would only create an offset (bias) on the vertical axis when the data were plotted using the reduced equation in the form

$$\ln\ln \frac{1}{1-f(x)} = \ln \alpha + B \ln (x-\mu) \qquad (2\text{-}C)$$

In a like manner the shape parameter (B) was arbitrary assigned a value of 1, primarily to facilitate calculations. The validity of the choice of these values was substantiated by the very high correlation coefficients (R) (see equation 3C) of the regression analysis lines of best fit, which in most cases was better than 0.95. In all cases, the location parameter or minimum value parameter (μ) was set equal to zero.

In equation form $R = M \dfrac{\sigma x}{\sigma y}$ (3-C)

where M = the slope of the line of best fit (l o b f)

σ_x = the standard deviation in the x direction of plotted data from the l o b f

σ_y = the standard deviation in the y direction of plotted data from the l o b f

APPENDIX E

PERCENTILES OF LWC VALUES

MVD - (um)	OBSERVED 99.9 LWC	WEIBULL 99.9 LWC	RECOMMENDED LWC	R	DATA MILES
TEMPERATURE 0°C to -15°C					
3-5	.50	.63	.50	.855	17
5-10	.60	.67	.67	.987	1380
10-15	1.28	1.11	1.28	.980	2269
15-20	1.37	1.34	1.60**	.983	1180
20-25	1.70	1.74	1.74	.993	486
30-35	.50	.48	.88**	.981	58
35-40	.40	.44	.44	.988	17
40-45	0	----	.13**	----	0*
45-50	.1	----	.1	----	17
50			.04**		
TEMPERATURE -15°C to -20°C					
5-10	.49	.45	.45	.982	144
10-15	.50	.61	.61	.996	55
15-20	.40	----	.66**	----	10*
20-25	.40	----	.58**	----	3*
25-30	.40	.40	.40	.999	14
30-35	.32	----	.32	----	5*
38			.04**		
TEMPERATURE -20°C to -25°C					
6-10	.30	.30	.30	.999	85
10-14	.40	.40	.40	.988	102
15			.04**		

*LIMITED DATA MILES

**FAIRED VALUES

APPENDIX F

FORTRAN COMPUTER PROGRAM FOR GRAPHICAL REPRODUCTION OF THE NEW CHARACTERIZATION

```
10*#RUN=(CORE=40K,ULIB) 975-751-06A/ADPLOT;975-751-06A/PLOTLIB#
20 DIMENSION C(10),Z(10),A(10),ZPTS(100),APTS(100), Y(10),XPTS(100),YPTS(100)
30 DIMENSION LAB1(27),LAB2(27),LAB3(20),LAB4(2),LAB5(28),LAB6(12)
40&,LAB7(12),LAB8(10),LAB9(1),LA10(6)
50 DATA XPTS/100*0.0/
60 DATA LAB1/65,84,77,79,83,80,72,69,73,67,32,73,67,73,78,71,32,67,79,78,
70&68,73,84,73,79,78,83/
80 DATA LAB2/71,82,79,85,78,68,32,76,69,86,69,76,32,84,79,32,49,48,44,
90&48,48,48,32,70,69,69,84/
100 DATA LAB3/76,73,81,85,73,68,32,87,65,84,69,82,32,67,79,78,84,69,78,
110&84/
120 DATA LAB5/77,69,68,73,65,78,32,86,79,76,85,77,69,32,68,73,65,77,
130&69,84,69,82,32,32,40,117,109,41/
140 DATA LAB6/45,50,48,32,116,111,32,45,50,53,32,67/
150 DATA LAB8/48,32,116,111,32,45,49,53,32,67/
160 DATA LAB7/45,49,53,32,116,111,32,45,50,48,32,67/
170 DATA LAB9/111/
180 DATA LA10/40,103,109,32,32,41/
190 DATA LAB4/45,51/
200 DATA L1,L3,L4,L5,L6,L7,L8,L9,L10/27,20,2,28,12,12,10,1,6/
210 DATA YPTS/100*0.0/
220 DATA ZPTS,APTS/200*0.0/
230 C0=-1.0522805
240 A0=-3.5238374
250 Z0=-9.1394344E-1
260 C(1)=2.9960598E-1
270 A(1)=1.2561859
280 Z(1)=4.3085546E-1
290 C(2)=-1.8312112E-2
300 A(2)=-1.6156104E-1
310 Z(2)=-4.5292582E-2
320 C(3)=4.6770813E-4
330 A(3)=1.0077214E-2
340 Z(3)=3.2568176E-3
350 C(4)=-4.7589022E-6
360 A(4)=-2.5568181E-4
370 Z(4)=-1.2806039E-4
380 Z(5)=2.416748E-6
390 Z(6)=-1.8602906E-8
400 Z(7)=2.7335108E-11
410 C(5)=5.0893099E-9
420 N = 5
430 M=4
440 MN=7
450 DO 10 IX=5,38,1
460 X=IX
470 YT = 0
480 DO 20 I=1,N
490  Y(I) = C(I)*X**I
500  YT = YT + Y(I)
510  20 CONTINUE
520  YX = YT + CO
530 XPTS(IX)=IX
540 YPTS(IX)=YX
550  10 CONTINUE
```

```
DO 110 IX=6,15,1
YT=0
DO 111 I=1,N
X=IX
Y(I)=A(I)*X**I
YT=YT+Y(I)
111 CONTINUE
YX=YT+A0
APTS(IX)=YX
110 CONTINUE
DO 120 IX=3,50,1
YT=0
DO 121 I=1,7
X=IX
Y(I)=Z(I)*X**I
YT=YT+Y(I)
121 CONTINUE
YX=YT+Z0
ZPTS(IX)=YX
XPTS(IX)=IX
120 CONTINUE
CALL INITT(30)
CALL BINITT
CALL NPTS(50)
CALL DLIMY(0.0,2.0)
CALL DLIMX(0.0,50.0)
CALL CHECK(XPTS,YPTS)
CALL DSPLAY(XPTS,YPTS)
CALL CPLOT(XPTS,ZPTS)
CALL CPLOT(XPTS,APTS)
CALL MOVABS(350,743)
CALL HLABEL(L1,LAB1)
CALL MOVABS(350,713)
CALL HLABEL(L1,LAB2)
CALL MOVABS(347,55)
CALL HLABEL(L5,LAB5)
CALL MOVABS(55,650)
CALL VLABEL(L3,LAB3)
CALL MOVABS(19,174)
CALL HLABEL(L10,LA10)
CALL MOVABS(64,183)
CALL HLABEL(L4,LAB4)
CALL MOVABS(374,234)
CALL HLABEL(L6,LAB6)
CALL MOVABS(604,585)
CALL HLABEL(L8,LAB8)
CALL MOVABS(479,330)
CALL HLABEL(L7,LAB7)
CALL MOVABS(625,348)
CALL HLABEL(L9,LAB9)
CALL MOVABS(723,605)
CALL HLABEL(L9,LAB9)
CALL MOVABS(518,250)
CALL HLABEL(L9,LAB9)
CALL TINPUT(I)
 STOP
END
```